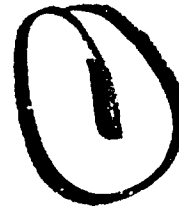| |
|---|
| |
| |
| **AD NUMBER** |
| AD487554 |
| NEW LIMITATION CHANGE |
| **TO**
Approved for public release, distribution unlimited |
| **FROM**
Distribution: Further dissemination only as directed by Chairman, Armed Services Explosives Safty Board, Attn: Department of Defense, Washington, DC, JUL 1966, or higher DoD authority. |
| **AUTHORITY** |
| DDESB ltr, 16 Jan 1974 |

BARRICADE EFFECTIVENESS EVALUATED FROM RECORDS OF ACCIDENTAL EXPLOSIONS
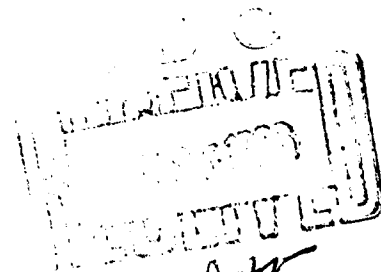
July 1966

ARMED SERVICES EXPLOSIVES SAFETY BOARD

DEPARTMENT OF DEFENSE

Washington, D. C.

(6) BARRICADE EFFECTIVENESS EVALUATED FROM

RECORDS OF ACCIDENTAL EXPLOSIONS,

(10) William S. Filler   Joseph M. Rossi   Harold R. J. Walsh
Naval Ordnance Laboratory   Picatinny Arsenal   Air Force Weapons Lab.
Silver Spring, Md.   Dover, N.J.   Albuquerque, N. M.

7 Jul 66

(12) 56 p.

ARMED SERVICES EXPLOSIVES SAFETY BOARD
DEPARTMENT OF DEFENSE
Washington, D. C.   034 850

ABSTRACT

This report presents the results of a 90-day literature study and analysis of data derived from accidental explosions and the implications of this data with respect to the effectiveness of barricades. Within the time allotted, as much data was studied as was readily available and in a reasonably usable form. The results, supported by a statistical analysis, indicate that for building damage caused by distant blast pressure effects, and maximum distance of fragment travel, a given explosive weight has the same effect whether the source is barricaded, the target is barricaded, or neither has a barricade. Separate studies were conducted on the durability of barricades, the distances at which various levels of damage occurred, the maximum distance of fragment dispersion, and the maximum distance of glass breakage caused by overpressure.

This paper is the result of a literature search carried out by a team assigned to the Armed Services Explosives Safety Board and presents a review of most of the available data bearing on the subject. It embodies a treatment of the subject that has not previously been accomplished and is considered a valuable addition to the available literature on barricade effectiveness.

This paper is a contribution to the investigation of barricade effectiveness and is part of a continuing effort being made by the Armed Services Explosives Safety Board in the interest of achieving the optimum degree of uniformity, utility, and economy in explosives safety regulations. Further tests and reviews of related scientific data are required in certain areas. Comments as to the technical content of this report and recommendations concerning further studies are earnestly solicited from all addresses.

The Board expresses its appreciation to the team members, Mr. William S. Filler, Department of the Navy; Mr. Harold R. J. Walsh, Department of the Air Force; and Mr. Joseph M. Rossi, Department of the Army. They worked diligently, both individually and collectively, to review an enormous amount of material and reduce it to a form of increased usefulness to the Board and to other organizations in future considerations of a technical problem of major importance to the Department of Defense and to the explosives industry.

CONTENTS

vii

Tables:

INTRODUCTION

A barricade is a construction feature used to provide for safety in the design of explosive facilities. It is a natural or artificial terrain feature partially or totally surrounding a building and is intended to reduce the effects of an accidental explosion on other buildings. Some protection is considered to be provided by a natural or man-made hill, by another structure, or sometimes by trees. In military manuals for the construction of explosives facilities, a barricade is more precisely defined as a massive wall or mound of given dimensions and materials. In general, these manuals provide for safety at explosives facilities by requiring specific spacings of other structures and facilities from a given quantity of explosives. The manuals require distances to be approximately doubled when neither the source nor the target building is barricaded.[1][2][3][4][5]

At facilities of the Department of Defense where large quantities of explosives are handled and stored, the use of barricades may require the expenditure of large sums of money, may involve the safety of many people, and may influence the acquisition of large land areas. Their use may also affect the ability of plants to produce at maximum capacity--an important strategic consideration in wartime. It is therefore essential that the Armed Services have available the best possible information upon which to base the design of facilities for storing, transporting, and handling of ammunition and other explosives.

CONTENT OF LITERATURE SEARCH

Appendix I contains a reproduction of a memorandum from the Assistant Secretary of Defense (I&L) that discusses the need for a study of barricade effectiveness, and directs that the initial step in the study shall be "a thorough literature search, compilation, and evaluation of data pertaining to the subject, from reports of tests and incidents currently available in both Government and industry." In compliance with this directive, a study team was established to conduct a search of the literature on barricade effectiveness. The effort was originally planned as a study of earlier reports and documents to evaluate the foundations for the use of barricades and to define their value more precisely by studying data from later accidents. A very desirable additional approach was deferred until a later date because of the need first to define the state of the art. That other approach is best described as a fundamental analysis (from a physical basis) of the

---

[1][2][3][4][5] See references on page 55.

effects of explosions and the durability of structures, bringing
to bear the extensive knowledge of blast effects and structural
engineering now available. Examples of this approach are such
individual studies as are found in reference 6, which describes
an after-the-fact blast analysis of a large-scale accidental
explosion, and reference 7, a design criteria analysis for blast
protection of a small-scale structure.

In the following sections, the literature search and the in-
formation it furnished on barricade usage is described. As a
means of defining terms, as well as providing a proper perspective,
the present usage of barricades based on quantity-distance tables
will be treated first. The next section describes the manner in
which the literature supports that usage. Subsequent sections out-
line the data search and evaluation of incident reports and give
a detailed treatment of the statistical analysis performed.

BARRICADE USAGE DEFINED

The consensus on the value of barricades is expressed in the
quantity-distance tables contained in various manuals of safety
practice. A general statement was made above that these manuals
provide for safety by requiring a certain spacing of other structures
and facilities from a given quantity of explosives. That is not
precisely correct. Actually, the tables only assert distances from
an explosion at which certain specified levels of damage are probably
risked. The protection desired for Department of Defense facilities
is delineated in House Document No. 199, 70th Congress, 1928.
Pertinent extracts from this are reproduced in appendix II.
Secondary or target facilities are divided into categories primarily
on the basis of their relationship to the explosives operation, and
quantity-distance tables are prepared for each category for the
risk considered appropriate.

The category given the greatest distance is known as inhabited
building, or those having least or no relationship to the explosives
facility. It includes parts of the explosives plant where no
explosives operations are performed as well as homes or businesses
owned by other parties but adjacent to the plant. These are expected
to be damaged, if at all, only to a minor extent. Two other cate-
gories, public railways and highways have somewhat lesser distances.
These lesser distances are permitted because of the possibility that
no vehicles may be present at the time of an accidental explosion
and partly because a stronger air blast would be required to damage
vehicles than frame buildings because of the great differences in

---

[6] [7] See references on page 55.

2

structural strength. The final categories, with respect to distance, consist of intraline and intermagazine distances. Buildings in which related explosives operatio s are performed are spaced at intraline distances. Because explosives are far more likely to explode accidentally while in process than while in storage, the intermagazine distances are less than the intraline, but both are much less than railway, highway, or inhabited building distances for any given quantity of mass-detonating explosive. In both, it is accepted that an accident will demolish or heavily damage buildings separated from the explosion by these distances, but it is believed that the presently required distances will prevent propagation of the explosion to the explosives in target buildings in an acceptable percentage of cases.

For each of the four defined categories of facilities and for certain related situations, American practice is to consider that barricades reduce the risk from mass-detonating explosives at a given distance. American quantity-distance tables incorporate this by specifying a different spacing for barricaded and unbarricaded facilities. When barricades are not present, the spacing listed is double that required in a similar category with barricades. There are certain approved designs for barricades, and their dimensions and orientation relative to the positions and shape of the other facilities is specified. However, in general, the specifications are dependent upon neither the weigl of explosive involved nor the degree to which a distance less than unbarricaded approaches the barricaded minimum. As an example, double-revetted barricades are used with weights of explosives up to 50,000 pounds and are built the same whether the facilities are at the exact barricaded distance specified or at any distance between this and the unbarricaded distance. The only decision required is the choice of the column which applies in the table of distances. Further, except in a limited sense and in the case of storage igloos, the distance does not depend on whether the site, the target, or both, are barricaded. If two structures are spaced at the unbarricaded distance or greater, no barricades are needed; if spaced any closer, down to the full barricaded distance, at least one barricade, as specified, must exist between them. The manuals also imply that the level of damage or risk to structures of a given category is irreducible. There is no discussion of methods for designing structures or barricades to better resist the effects of an explosion, in cases where a greater level of protection is essential at a given distance than that accepted by the quantity-distance tables, or where a structure must be located closer to the potential source of explosion than the barricaded distance.

3

It will be observed that the quantity-distance tables consider
that barricades furnish protection over a wide range of damage
levels and against several damage mechanisms. At the inhabited
building distance, most damage is a result of blast pressures of
low intensity. Since barricaded-distance tables permit using half
as great a distance, they lead some observers to erroneously assume
that the damage will be no greater than that at the unbarricaded
distance, and thus they must be considered to make a great change
in low-level air blast pressures. Actually, since air blast
pressures scale roughly with the inverse square of the distance,
it is assumed that the barricade changes this air blast parameter
by a factor of three or four from what it would otherwise have been
at the unbarricaded inhabited building distance. At intraline and
intermagazine distances for mass-detonating explosives, a similar
halving of distance to a certain level of damage is allowed, but
at a much higher damage level related more to blast impulse than
to pressure. Also, for these intraline and intermagazine categories,
many assume that a reduction is made to the same extent in air blast
values as in the probability of fragment and debris strikes. This
latter mechanism is much more closely involved in the propagation of
an explosion than is the air blast itself. The tables do not in
fact consider these to scale in the same way as the air blast, since
in the description of damage at inhabited building distances it is
mentioned that damage from fragments will be negligible except at
distances appropriate to small quantities of explosives, where
blast damage is predicted to be uniformly minor.

In summary, quantity-distance tables for mass-detonating
explosives assume that barricades furnish protection over a wide
range of weights of explosives and of distances and against a
variety of damage mechanisms. The mechanisms include blast pressure,
blast impulse, the spread of fragments, and the spread of fires.
The construction of the barricade and the manner in which it is
assumed to furnish protection do not change in accordance with
explosive weight, actual or scaled distance, or damage mechanism.

BARRICADE EFFECTIVENESS IN THE LITERATURE

It is now desired to describe the extent to which the literature
supported the usage of barricades described in the previous section.
First, it should be said that such literature is very limited in
extent. The single most important document, History of Explosions,[1]
is based on a study made 56 years ago, which has had enormous
influence and, along with several minor revisions since, is the
basis of American practice. The study on which the document was

---

[1] See reference on page 55.

4

based, along with the several other studies described below, had as its main goal the establishment of safe inhabited building distances. The findings were presented as the American Table of Distances (ATD). The ATD established the practice of doubling required distances to buildings when barricades are not used. Yet, surprisingly, no tests, analyses, or other evidence are provided in the History of Explosions to support the idea of barricade effectiveness or in fact to evaluate it in any way.

The study included data from many barricaded and unbarricaded explosions plotted together, but no attempt was made to compare these with each other. The data points were chosen to represent a distance bound to buildings receiving substantial structural damage, which was by its definition a level very similar to that now predicted for inhabited buildings at barricaded distances. The purpose of this and similar studies was only to determine the values for that specific category of risk, or column in a quantity-distance table. No attempt was made in these previous studies, by curve-fitting or by any other statistical method, to find whether or not the barricaded points indicated consistently different distances from those indicated by the unbarricaded points. The procedure used when the ATD was formulated was described very well by Robinson,[14] as follows:

> "In determining the values for the American Table of Distances...The method consisted in plotting the maximum reported distance against the weight of explosive involved, and those who prepared the table elected to plot the 58 cases where the explosion was barricaded. In order, however, to include the 34 cases where there was no shielding, for reasons which no doubt appeared sound to them in 1910, but which at the present time seem without any foundation whatever, they divided the actual reported distance by two and so plotted them."

Actually, it appears that past usage was based on so firm a belief in the value of barricades that people presumed it in their initial approach to the problem, never performed a test to evaluate it, and ended by feeling it was a result of their study. The story of the workman who hid behind a buggy full of nitroglycerin during a snowball fight exemplifies this belief, seemingly rooted in instinctive feeling, that any screen between a person and a hazard makes him safer.

Two studies were made during World War II that included specific attempts to evaluate barricade effectiveness based on accident data.[8,9] In both cases, the presence of barricades was found to have no effect on damage-distance relationships. Also, an unpublished postwar effort,[10]

8 9 10 14 See references on page 55 and 56.

which was the most detailed accident data study to that time, did not attempt to evaluate barricade effectiveness. Curiously, it ignored the matter entirely. It treated the data as if barricades did not play a role--without presenting any evidence or discussion to support this sweeping assumption. These last three efforts do not appear to have affected usage with regard to barricades in any significant manner.

One recent British document[11] that came to our attention reported a controlled attempt to determine experimentally the effect of a barricade on the pressure of the blast wave for inhabited building distances. In that study, pressures were not found to be reduced by the presence of the barricade.

A matter of special interest is the fact that data have never been plotted for a large number of accidents except to determine inhabited building distance. This approach is so firmly established in the American literature that no other possibility is discussed. Thus, in his book, The Science of High Explosives, Cook[12] describes the advanced state of the art of explosives safety merely with a discussion of the manner in which accident data had been used to improve the values for inhabited building distances down through the years. He mentions the contributions made to this process by various experts, including Robinson, who was quoted earlier. Neither he nor anyone else was found in the course of our study to have mentioned the possibility either that accident data might also be used to establish a value for intraline or intermagazine distance or that the data with and without barricades from many accidents might be compared to establish their value for these categories.

(It should be mentioned, however, that a valuable British study was made of building damage in various categories resulting from bombing of British cities.[13])

There have been studies performed to check on intraline, public highway, and intermagazine distances. However, these uniformly consisted of an analysis of data from a single accident. One good example is the thorough studies of the Port Chicago explosion, and many others are at hand. In a number of cases, efforts were made to study a single damage mechanism, such as the fragment pattern or the spread of fires. These valuable studies were competent and thorough and, among other conclusions, often state that the barricades had been shown to have affected the fragment pattern or other mechanism studied. Individually, however, they were done by different people in different ways, using data gathered by different methods. In this situation, even if a sufficient number of barricaded and un-barricaded cases had been studied separately, it would not be possible

---

11 12 13See references pages 55 and 56.

6

to compare the material in any one study against another with a different arrangement of barricades. Too, such commendable effort has been applied to only a f w accidents.

In many past accidents, the primary purpose of the investigation was to determine the specific cause of the explosion. This is particularly true of a required formal investigation. Only information bearing upon cause was gathered, and the data were analyzed only in ways bearing on that question. When one considers the fact that one finds so few accidents in which the effectiveness of barricades was studied or in which data were carefully recorded for the bearing they might have on the question, the source of the present usage of barricades is obvious. Their value has been assumed and generally accepted, and since it is not in the nature of things for two accidents to be identical in every respect except for the presence or absence of a barricade, very few persons have objectively observed any results in accidents which caused them to doubt the value of barricades. Therefore, their value has rarely been systematically studied.

DATA AND ANALYTICAL METHODS USED

SCOPE AND LIMITATIONS

As a major part of this effort, all available records from past explosives accidents were studied to gather any data that appeared likely to demonstrate or serve as a test of barricade effectiveness. Each method of analysis is discussed in detail in the next section, and only the general information applicable to all methods is given in this section.

The criteria by which the analytical methods were chosen is a very important general point. Certain individual analyses involved damage of levels and types against which one might wish to protect, for which quantity-distance tables are written specifically to provide certain degrees of protection. Other methods involve effects for which one does not normally attempt to provide protection and which may therefore seem rather trivial. However, both types have a place in a study intended primarily to determine the degree to which barricades influence the effects of an explosion. Each method of analysis was chosen to make use of an item of information that was reported validly, accurately, and unambiguously in a large enough number of accident reports, so that its values could be compared for a sufficient number of barricaded and unbarricaded cases. Further, the effects chosen had to be those which appeared to have a direct physical relationship with the explosion and could reasonably be expected to be influenced by a barricade in some rational and consistent way.

7

These criteria eliminated certain types of information which, if analyzed, would have great interest and value for everyone involved in explosives safety. The question of whether barricades change the pattern of low-angle, high-velocity fragments could not be studied simply because accident reports contain insufficient relevant information. They do contain much information on fragments but rarely identify their trajectory. It would also be desirable to identify the distance within which fragment density was above some safe level, but this is seldom reported in a quantitative and useful way. Too often, it requires one to guess the intent and basis of judgment of the many reporters who state that few fragments fell beyond some distance or that most fell within a certain distance. Either statement may be based on the fact that somewhere between 50 and 99 percent fell within that distance. Even when detailed fragment maps are given, they usually list only identifiable source hardware and leave out most debris such as clods of earth and fragments of concrete.

The use of the accident records to obtain a measured value of the extent to which the barricade affects the chance of propagation to other explosives is even less possible, because the explosion usually destroys all evidence of the mechanism and timing of the second detonation. Further, adjacent stacks of explosives are usually found only in explosives storage or manufacturing plants, most of which are barricaded; therefore, unbarricaded instances of this type are very rare. Because of the scarcity of valid data involving such facilities, it was also not possible to study statistically the extent to which effects were mitigated in plants having buildings specifically designed to resist the various effects produced by external explosions. Igloos, for example, were treated as merely barricaded.

BUILDING DAMAGE STUDY

In the study of damage to individual buildings (p. 20) each building was classified into one of five damage categories, A through E, ranging from "total destruction" to "minor." This type of analysis is related to the quantity-distance plots from which came the ATD and the similar efforts of Robinson[14] and Ilsley.[10] In the present study, however, five categories of damage are considered instead of one, and actual distances are not used. Rather, the distance (R) was divided by the cube root of the explosive weight (W), a commonly used technique, making the plot nondimensional as far as weight is concerned. This scaling method coupled with the five damage categories results in a simplification of the data presentation, which in turn permits a much more comprehensive analysis than has been achieved

───────────

[10] [14] See references pages 55 and 56.

heretofore. The scaled distance, conventionally referred to as λ was determined for each damaged building and plotted against the damage category. Within each damage category, the items were separated according to whether or not barricading was involved. This plot provides an overview of the trend of damage as a function of distance. At the same time, it makes possible an evaluation of the effect of barricades in five categories covering the full range of building damage possibilities. The levels of damage range from minor, or less than that expected at the inhabited building distance, to severe, which is even greater than that expected at intermagazine distances. In effect, certain levels of damage are thoroughly studied which are not known to have been so thoroughly studied before, and the comparison of barricaded against unbarricaded cases through out all levels is also a new approach.

OTHER EFFECTS STUDIED

Other efforts included studies of the maximum distance of glass breakage, of fragment dispersion, of distance to one chosen level of structural damage, and of the survivability of barricades themselves. The maximum fragment and glass breakage distances are obviously subjects which were studied not because they might be used immediately as safety criteria, but only because they might indicate the effectiveness of barricades. These particular damage studies differed from those described previously in that here, in addition to studying the effect of the presence or absence of a barricade, a third category was added for cases in which a barricade that was present was destroyed. The study of the survivability of the barricades themselves was performed as a means of presenting for the first time information on their strength, which might be useful to a designer of such facilities.

In all of these, actual rather than scaled distances were used, so that consideration of a few of the many other parameters involved in accident data might be attempted. One of these attempts involved the hypothesis that the destruction of a barricade may absorb a fixed quantity of energy, irrespective of the total amount present in an explosion. Such an effect could be detected as a change in slope of the data where quantities of explosives are plotted against actual distance, but would appear only as scatter on a plot where reduced distance, λ, was the variable. The other parameters whose effects were intended to be isolated included the weather, the geometry and height above ground of the exploding mass, and the extent of confinement of the explosive by its container and building, as well as the actual type of explosive rather than merely its weight.

9

Both the maximum distance of glass breakage and of fragment travel had the advantage of being recorded often. In addition, each is an objective quantity not subject to the judgment of the recorder, as are statements that glass breakage was severe or that fragments were dense to a certain distance. Of course, each such report is subject to error or understatement, since there may have been no windows present beyond a certain distance, or the most distant fragment may not have been found. Each, however, is a phenomenon which would be accurately reported and valid and which might be expected to be affected by the presence and survival of barricades.

In the study of the specific level of building damage, the level chosen for detailed analysis was the most easily identifiable range, that above which an ordinary wooden frame building would have damage at least to main supporting members and below which it would not (see Appendix B).

To summarize, the approach used was to isolate an effect which might be influenced by the presence of barricades and to devise some rules by which data were plotted to find whether the change was evident. All of the data were collected and summarized, with only validity and consistency of reporting being used to determine whether or not a particular item of information should be extracted from the files. The data were then applied in accordance with the chosen rules. The effect of barricades would be indicated by a difference in the distances of the barricaded and unbarricaded cases in each of the studies.

COLLECTION OF DATA--SOURCES, METHODS, CRITERIA

A number of governmental and private organizations assisted in this study by opening their files to a search for data on accidental explosions. These included the offices responsible for safety in each of the Armed Services, the Armed Services Explosives Safety Board (ASESB), the Institute of Makers of Explosives, the Atlas Chemical Industries, the Hercules Powder Company, the American Cyanamid Corporation, and the E. I. duPont de Nemours & Co., as principal parties. The commercial organizations kindly allowed full access to their plant accident files because of their intense concern for plant and public safety. Most reports on Service incidents were found to be already available to us in the ASESB files. Information was also gained from explosion research reports, from earlier studies of accident data, and from discussions with a number of experts in the Government and in private industry. As a result of this cooperation,

10

more than 5,000 separately filed items involving accidental explosions were searched. These included all of the information which the several organizations had collected during this century.

The incidents ranged from the accidental ignition of a single fuse to the catastrophic detonation of all explosives in a plant or ship. Naturally, the incidents were not all of interest. Conveniently, the larger incidents of particular interest to us tended to be the ones included as items in the files of several organizations and stored even after the paper became difficult to handle and to read. Thus, the file search resulted in the collection of data on 252 cases falling in the range of interest and having enough information to make the collection of data worthwhile.

A detonation of 250 pounds of explosives was chosen as a lower limit. In the weight range below that amount, nearby structures will suffer significant damage from which useful information might be obtained. However, the damaged buildings would be so close to the source that the measured and recorded distances of the type in accident reports would be expected to introduce unacceptable errors. The lack of precision arises in part from reporting distances in round numbers, but even more from the geometry. The rapid change in pressure as a function of distance for such relatively small charge weight will cause great differences in loading on the near and far parts of a building. The cases of interest, then, were those involving 250 pounds up to the maximum found, which was well over 1,000 tons in a few cases.

Early in the examination of the files, a standard blank form was prepared for recording all data of possible value from each incident. This worksheet, used in the collection of data, is illustrated in Figure 1. It was designed for a concise collection of all information which might bear on the size, efficiency, and physical effects of an accidental explosion. Few incidents were ever described completely enough to permit filling out all the blanks. In some cases, data were rendered unusable by the absence of key information, for example those where no information on the total quantity of explosives was given or where physical effects were not described in a manner useful to this study. This comment is no reflection on those who prepared the accident reports; their interest was normally in determining the cause of the accident so that repetitions could be avoided, and they usually had done this very well. In fact, much of the information needed for this study was in the files primarily because it bore on the cause of the accident or because of the apparent effectiveness of the protection provided to employees, whether by design or not. As a result, in many cases, the detail

11

Place of Incident_____ Date_____File No._____

Cost_____Fatalities_____ Injuries_____

Height of Burst_____

Crater _____ Radius_____ Depth_____

Fragment Distance_____ Maximum_____ High Density_____

Casualty Distance_____ Maximum_____ High Density_____

Glass Breakage Distance_____ Maximum_____ Complete_____

Elevation_____ Weather_____

EXPLOSIVE

Type_____ Total Present_____

Maximum Single Detonation_____ Total Detonation_____

Multiple Detonations_____

Confinement at Source_____

Source Barricade, Building, or Screen_____

_____

Evaluated TNT-Equivalent Weight_____

DAMAGE

Table Distances: Unbarricaded_____ Intraline_____ Inhabited_____

Item[1]	Description[2]	Distance		Effects		Construction and Damage
		Feet	λ	PSI	PSI-Sec	

[1] Negative sign following item indicates less than required distance
Positive sign following item indicates proper distance

[2] B indicates target barricaded
U indicates target unbarricaded

Figure 1. Sample Worksheet

12

used in finding the cause of the accident made possible filling the blanks on the worksheet by such detective work as measuring and estimating distances from fragment maps or photographs. A particular incident in the range of interest was rejected only if no way of establishing valid data from the evidence was at hand.

The raw data as recorded on the original form cannot be published in its entirety in this report because of the right of privacy of the organizations which permitted it to be gathered. There is no intention of implying negligence or disregard of safety on the part of private industry or governmental organizations. On the contrary, governmental installations and private industry maintain an excellent safety record in manufacturing and storing explosives. However, certain data found could reveal proprietary information concerning mixing and batching processes or proportions to one who knew which item he needed to know. In other cases, the actual mixture involved was classified for reasons of national security. Therefore, since all details of many cases could not be made public, it appears better to reveal none. In this manner, the details of those instances which must be concealed cannot be identified on charts and graphs. Unfortunately, this makes impossible any identification of individual data points with their sources, whether from raw files or from earlier reports.

A further unfortunate effect of publishing none of the raw data is that the detail with which it was gathered cannot be demonstrated as a means of promoting confidence in the overall results. For example, rather than giving a mere categorical statement that a building was or was not barricaded, the type, size, and degree of survival of a barricade and of the building within it were described in as much detail as was available. When the description included information on where openings in the barricade were, what its type of construction was, and whether or not it had been destroyed, a determination could be made whether it stood between the source and another building whose direction was known. The construction of target buildings and the extent to which they themselves were barricaded was also recorded. Certain items such as the type and form of crater, the type of explosive, and reports of multiple detonations were recorded because they could help to decide the probable maximum size of essentially simultaneous detonations. Notes on weather and terrain were included because of possible effects on air blast parameters and asymmetry in the damage pattern. In general, notes were included on anything found in the record that appeared to indicate the presence of an unusual condition that would produce peculiar and incomparable results. It was intended that the worksheets should give as accurate a picture of the significant details of the explosion

as could be obtained from the records. However, it is believed that
the potential of the worksheets for analysis has not been exhausted
by this study. In fact, the worksheets could be of considerable
value for related studies and as a source guide to the original
accident reports. When such a need arises, these can be made available
from the ASESB files, subject to security and proprietary control.

DETAILED DISCUSSION OF ANALYSES

STUDIES CONDUCTED

The several ways in which data from accidental explosions were
studied are described in detail in this section. Each study is
presented in a separate section; section subjects are as follows:

1. Durability of barricade types

2. Distance to individual building damage of various categories

3. Maximum fragment distance

4. Maximum distance of glass breakage

5. Distance to comparable structural damage

In the studies described in sections 3, 4, and 5, only those
cases were used in which information on the barricade and its survival
was complete. This requirement was in addition to the rule followed
in all studies, that the damage information be sufficiently detailed
and apparently accurate in all other respects. By applying these
criteria, the amount of usable data was greatly reduced. The original
252 cases were reduced to a selected group of only 86. Of these, in
30 cases there was no barricade at all; in 24 cases the barricade
survived but suffered erosion and cracking of the facing; in the
remaining 32, the barricade was completely removed. tipped over, or
a large section of the facing and at least part of the backing were
gone. These different conditions are identified as "unbarricaded,"
"barricade survived," and "barricade destroyed," respectively.

DURABILITY OF BARRICADE TYPES

From the study of those cases in which the barricades at the
source of the explosion were well described, an attempt was made to
determine the extent to which each type of barricade survived
explosions of various sizes. The pattern of failure or damage to

14

the barricade was of particular interest, as well as the weight of explosives causing complete destruction. The weight of the explosion that a barricade survived appears to depend, as might be expected, on its construction and on the extent to which the source was confined by barricades. For the purposes of this discussion, barricades are considered to be of five types, namely, the crib, Rapauno, or double-revetted; the mound or single-revetted; natural barricades; other intervening terrain features; and igloos.

Crib, Rapauno, or Double-Revetted Barricades

Weakest of all barricades are the crib or Rapauno type. These are walls of soil held between a nearly vertical sheeting of wood or concrete on each side, so that their top is typically perhaps three feet and the base 12 feet wide for a wall 20 feet high. Because of settling or weathering, the soil does not usually fill the barricade to its full height except when it is new. Since, even when it was recorded, this void usually made small change in its height, all were here assumed to be of full designed height. Actually, such changes cannot be expected to affect the end result greatly.

When an accidental explosion took place, damage to the cribs increased with explosive weight and followed a certain pattern. The least damage consisted of breaking and disordering of the interior facing, together with erosion of the earth behind it to some depth down from the top. The exterior facing also was broken off, usually being completely gone for a greater distance down from the top than the interior facing. Thus, the soil was left with an upper surface that sloped steeply downward from the inner to the outer face, but usually below both. As the damage level increased, the depth of this soil surface came further down, until finally the barricade was gone completely down to ground level or below (when a crater extended to its location). The damage varied with the distance of each part of the wall from the explosion, so that often the middle parts of straight walls were completely gone while the corners largely remained.

When an explosion was surrounded by barricades on all sides, the greatest high-explosive blast that caused only small damage to the crib walls was 250 pounds, while explosions as small as 1,325 pounds completely removed them. In one case they survived an 850-pound explosion, but the explosives may not have detonated simultaneously. Where several types of barricades surrounded a single source, the crib parts suffered less damage near their connections to other types of walls than they normally would at the distance concerned.

15

When the barricades were built on fewer than four sides, barricade damage was reduced. A part of the concrete facing and foundation often were in place - although badly broken and tipped - after explosions as great as 3,000 pounds. Cribs near an explosion appear to act as open sides by failing very rapidly, thereby reducing damage on more distant parts. Thus, in one instance where a 1,300-pound explosion was surrounded by cribs, the walls at 20 feet were completely gone, but those at 45 feet had received small damage. In general, when some walls were weak, other sections of the barricade received less damage than similar sections suffered in other accidents with similar explosive weights where all other sides were closed with more durable types at comparable distances.

Mounds, or Single-Revetted Barricades

Another type of artificial barricade has sheeting on only the one side nearer the explosion, and is here called a mound. Often these are called single-revetted barricades, while the cribs discussed above are double revetted The inner side is sheeted to a slope equivalent to that of a crib, while the outer side is at a slope at which the available soil is stable. Thus they are much more massive than crits, having a base perhaps 45 feet wide for a height of 20 feet and a top width of three feet. Explosions caused breakage of the facing of the mounds and erosion of the earth behind the facing, just as they did when a crib type barricade was used. The remaining part was left with an upper surface flatter than that of a crib, but still sloping down with increased distance from the explosion. As the weight of the explosion increased, the depth cut away also increased, but the upper surface became flatter until finally complete destruction was characterized by the mound being level with the ground from the inner face out to a small pile of material left in place at the far edge. Sometimes the crater extended into the leveled area.

Sufficient examples were found to relate the damage trend to charge size. Detonations of 500 pounds of high explosives produced negligible erosion when another side was open or was barricaded by a crib that blew down, but 600 pounds produced significant erosion when mounds fully surrounded the explosion. The upper half or two-thirds of the mound was removed by an explosion of 1,000 pounds, and as little as 1,200 pounds caused complete destruction as described above. In some cases, most of the height survived explosions as great as 4,000 pounds, and up to 10,000 pounds if one or more sides were open; but in such cases the records generally indicated that the explosion was at second-story level or above.

Natural Barricades

To simplify discussion, natural barricades are limited here to those whose tops are the original ground surface and which have an inner slope with some sort of near-vertical facing. (This definition is more restrictive than in some manuals. In later paragraphs, the term "faced natural earth barricades" is used to distinguish this kind of barricade from hills or belts of trees, which are sometimes considered natural barricades.) Natural barricades often are constructed by building the structure within a level area cut into the face of a hill, the sides of the cut being nearly vertical and faced usually with mass concrete, sometimes with wood cribbing. Occasionally equivalent barricading is provided by keeping the explosive in the basement of a building on level ground or cut into a slope, the barricade facing acting as the supporting wall.

Here, we are concerned with the survivability of the natural barricade, or from ground level downward. On a hillside, this has one open side, one level-topped side of full height, and two sloping sides. Occasionally the open and sloping sides are close to full height with cribs or mounds whose survivability was discussed earlier. It was found that the natural barricade was chewed away from the top down just as the mound was, but that larger detonations were required to produce this erosion, and the remaining surface was different. Also, destruction and removal of the facing below the eroded surface was more complete. The eroded surface typically sloped upward as distance from the facing increased, much as the slope of a crater in the same soil would.

Below a weight of approximately 1,000 pounds of explosive, damage is limited primarily to breakage of the facing below the natural ground surface, with some throwout. At a weight of approximately 1,000 pounds of explosive, even strong facing is disintegrated, large amounts of it are gone, and the typical crater surface has been chewed far enough down in the facing to involve some of the earth behind it. At a weight of 7,500 pounds of explosive, most of the facing is gone, and the crater surface may extend in places from the inner face near the bottom of the wall up to the ground surface. As weights increase through the range of 1,500 to 7,500 pounds, the breakage of the remaining facing and its removal or displacement from the original position become greater. The details of the final configuration vary with the height of the charge above the floor and its distance from the wall, but the intent here is to describe the geometry of the failure as it varies with explosive weight.

17

Terrain Features

Natural hills or ridges, without alteration, and heavy belts of
trees are considered to be barricades in some manuals and usage.
Although difficult to assess because of a lack of information on
their original condition, some attempt was made to estimate their
durability. Natural hills are usually undamaged even in very large
explosions, apparently because the slope is flatter and the hill is
farther from the charge than a crater surface would be in a faced
natural earth barricade. Trees also appear to be fairly durable.
Some which have stood as close as 50 feet to a 1,500-pound explosion,
otherwise unbarricaded, have remained standing although suffering
fragment damage and having many branches stripped. Unfortunately,
most information on both trees and hills is very qualitative, being
taken only from photographs, since few have recorded the distance
to trees or the before-and-after surface of a natural hill.

Igloos

Igloos are built for storage of great quantities of explosives
that fill their volume, and are not expected to survive any explosion
when filled to their design weight. However, cases were found in
which accidents occurred in nearly empty igloos, and from these
some observations were made on their pattern of failure. In all
cases, the igloos had a standard reinforced concrete circular arch
as a roof, covered with a few feet of earth. Some distance above
the floor, the earth fill and concrete wall become of such a width
and shape that from there down they greatly resemble a mound barricade.

In even the smallest explosions, the roof was completely removed
down to the point where the mound shape began. Below that point,
instead of being eroded and fragmented like mounds, the igloo wall
usually was shoved horizontally outward as a broken but identifiable
mass, sliding on its contact with the ground surface. Often the wall
moved tens of feet but remained nearly intact. Also, the floors
usually were intact and without craters in those explosions where
the walls were shoved out but standing. For greater quantities,
the site would consist only of a huge crater with hardly a trace of
the floor and walls. These accidents usually involved ordnance items
in crates and on skids rather than a homogeneous mass of explosive,
which would reduce the initial pressures, of course. Judging from
photographs of several such explosions, it appears that the floor
and wall structure was not torn apart or cratered locally until the
total weight of explosive was great enough to produce a crater larger
than the floor area.

18

Failure in the form of roof removal and wall shoving occurred in explosions in a range from 1,150 to 45,000 pounds of high explosives. In explosions of 100,000 pounds or more, however, the entire site became a crater.

Summary and Additional Comments

During the course of this study, the observations and opinions summarized below were developed on the mechanisms by which accidental explosions damage barricades. The barricade is itself damaged by erosion from blast waves which follow its surface contour, by extreme pressure crushing its facing, and by shearing or tension failures within it that permit large sections of it to move. These effects are to be expected, but are not the ones of interest here; rather the nature of the explosion itself and the pattern of debris will be considered.

In providing safety precautions against the effect of accidental explosions, it is common to consider that all of the explosives present at a source will detonate simultaneously in a single homogeneous mass. It was found that such treatment was appropriate for the more distant effects studied. For such close-in effects as damage to the barricades, however, the fact that the explosives usually are in several piles seems to be of importance. Certain effects indicate that some period of time separates explosions of the piles or that the detonation is not ideal. If detonation were ideal, the explosion could be analyzed on the basis of supersonic shocks, and the fact that barricades existed only on a few sides of an explosion would have little effect on the damage to those present (contrary to what is actually observed). Further, erosion of the surface often appeared very great compared to that expected from a single shock. From all of this, it is apparent that anyone who is attempting to analyze the close-in effects of such explosions should consider the actual geometry of the several charges and consider an appropriate time interval in which the explosion can propagate from one to another.

The debris torn from barricades, often large in volume, spreads over a wide area. From photographs and fragment maps, it appears to be scattered at least as broadly as the material would be from a crater caused by an explosion of the same size on a level earth surface. Only in those cases in which the walls of an igloo were pushed for some distance as an intact mass did the barricade fragments appear to move more slowly and for lesser distances than crater debris. In all other cases, debris from the barricades may increase greatly the density of high-velocity fragments.

19

In view of the fact that barricades always suffered damage to the great extent indicated above, comment should be made on the manner in which it was decided that a barricade survived, for the purposes of those studies in which the effect of survival was considered. If the barricade was still present as a significant terrain feature, it was considered to have survived. For example, if something less than a third of its top was missing, the remaining pile of material was considered as a surviving barricade. Natural hills and trees still visible as a thick belt were also considered to have survived, although they occurred in only a few of the cases studied. In effect, if a barricade was still able to present a significant obstacle to the close-in blast flow at the end of its long duration, it was categorized as having survived in those studies. The decision had no relationship to the cost of repair or to the size of detonation for which these types are used as protection. For example, the crib type is destroyed by a very small percentage of the 50,000 pounds that manuals permit to be stored behind it.

DISTANCE TO INDIVIDUAL BUILDING DAMAGE OF VARIOUS CATEGORIES

The data on distances to all buildings that received damage as defined in the five categories was entered on a number of tabular displays, one of which is figure 2. From these, the bar chart shown in figure 3 was prepared to compare the medians of the plotted values in each category for several combinations of barricaded or unbarricaded sources and targets. The general nature of the information obtained from these figures and also from a statistical analysis of the data is presented here.

The tabular display, figure 2, consists of five sets of columns corresponding to the damage categories, within each of which are two columns with headings to indicate whether or not barricades were present. For each damaged building, a data point was entered in the appropriate column at a vertical location corresponding to its reduced distance, λ, from the source. From this figure one can read for each building its distance from the explosion, its category of damage, and the presence or absence of barricades. Here, the test of the effectiveness of barricades in each category will consist of whether the greater distance occurs in the barricaded or unbarricaded case. Information on whether the barricades were at both the source and target, or at only one of the two, is also coded into this plot.

The bases on which this chart was constructed are as follows:

1. From the 252 data sheets prepared from the file search, a total of 134 data sheets were judged to contain some information

Figure 2. Scatter plot for categories of damage.
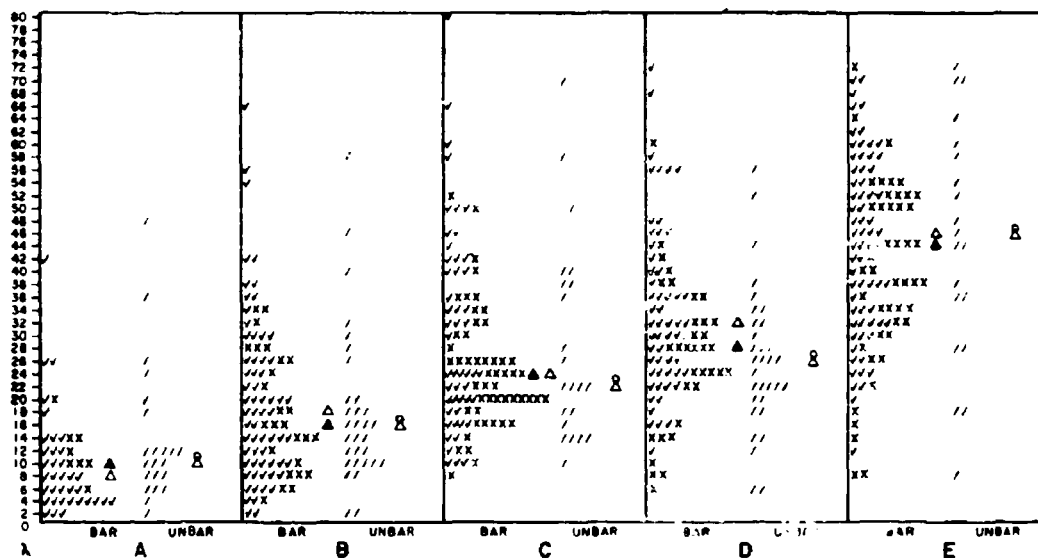
A DEMOLISHED, NOT STANDING

B DAMAGE SEVERE: STANDING, BUT SUBSTANTIALLY DESTROYED, SOME WALLS GONE

C MODERATE DAMAGE: WALLS BULGED, ROOF CRACKED OR BULGED, STUDS AND RAFTERS BROKEN

D SLIGHT DAMAGE: DOORS, SASHES, OR FRAMES REMOVED; PLASTER AND WALLBOARD BROKEN; SHINGLES OR SIDING OFF

E MINOR DAMAGE FROM GLASS OR MISCELLANEOUS SMALL ITEMS (similar to that resulting from a high wind)

✓ ONE BARRICADE, EITHER AT SOURCE OR AT TARGET

X SOURCE AND TARGET BARRICADED

▲ MEDIAN: SOURCE AND TARGET BARRICADED

△ MEDIAN: SOURCE OR TARGET BARRICADED

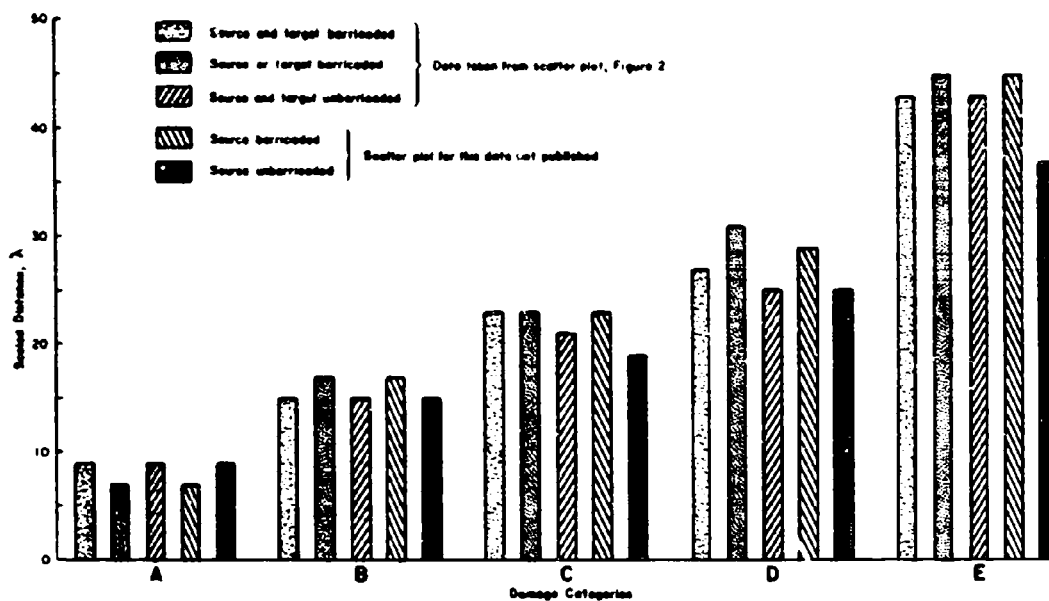𝔅 MEDIAN: SOURCE AND TARGET UNBARRICADED

21

Figure 3. Median distances for categories of damage.

useful to the purpose of the chart. The excluded material had one or more essential pieces of information missing. The plot is for high explosives only. Other explosives, e.g., black powder and propellants, yielded data in such a limited amount and with such a wide scatter when plotted separately that significant results could not be obtained, and therefore the plot is not included here.

2. When the data consisted only of a statement that a certain type of damage (moderate, light, etc.) occurred out to a given distance, it was not used for reasons of consistency. Only informatic on individual buildings was used. The former data representing the outer bound for the various classifications of damage were considered to be of a different type.

3. The damage categories are similar to those used in other studies. These are as follows:

   a. Category A. Demolished, not standing.

   b. Category B. Damage severe; standing, but substantially destroyed, some walls gone.

   c. Category C. Moderate damage; walls bulged, roof cracked or bulged, studs and rafters broken.

   d. Category D. Slight damage; doors, sashes, or frames removed; plaster and wallboard broken; shingles or siding off.

   e. Category E. Minor damage to glass or miscellaneous small items (similar to that resulting from a high wind).

Categories B, C, and D are essentially the same as the three used in The Effects of Nuclear Weapons.[15] In evaluating each item, the descriptions by the reporting activity were generally accepted as reported. However, a degree of judgment was involved in some cases in which the description of damage was ambiguous or the terminology not consistent.

4. The distance given was divided by the cube root of the weight of the explosives. The weight was taken to be the amount of high explosives actually exploded, to the extent that this could be determined from descriptions of munitions or of preceding fires when these were involved. In multiple explosions the maximum single explosion was used.

---

[15] See reference on page 56.

23

5. A source or target building was considered barricaded only when the report indicated that the barricade appeared to be of an approved design, an adequate earth mound, or natural earth topography. No credit was given when protection was reported to have been afforded by the presence of railroad cars, light buildings, or trees.

6. When it was possible to orient either the barricade at the source or the barricade at the target, credit for barricading was given only when the barricade actually stood between the source and the target. Data points were discarded when the barricade was not between the source and target.

7. All data points selected for this plot refer to fairly standard building construction. No use was made of the few instances which indicated that the explosion source involved extra protection; i.e., 18- to 30-inch reinforced concrete operational shields or 12-inch reinforced concrete substantial dividing walls, with or without barricades.

8. It should be noted that the reduced distance, λ, is plotted at regular intervals up to λ = 80. Beyond this distance there were a number of points. However, these were very widely scattered, some out to a very great distance. Since this occurred in both the barricaded and unbarricaded cases, it was felt reasonable to discard this data for reasons of convenience. Since the excluded data was almost entirely in the E category, it is probably well represented as a class in the study of maximum distance for glass breakage.

Using similar rules, tabular displays were also prepared based upon other combinations of source and target barricading. These are not presented in the report, however. Instead, for ease of comparison, the results of all such tabular displays are presented in a composite bar graph, figure 3. On this bar graph, the length of each bar represents the median value for the scaled distance in a column on some tabular display. Within each category, five possible combinations of source and/or target barricading are represented by bars.

On the graphical display, figure 2, the data is seen to be widely scattered, except that in each column there is a short length in which the majority of data points are concentrated. This concentration of data points is at λ values that increase as the category of damage decreases in severity and importance. In each category, there is substantially more data in the barricaded than in the unbarricaded column, but there does not appear to be any marked difference in the distance to the concentration of data points in the two columns under any category.

24

As a simple and convenient means of crystallizing the main trends of data of this sort, the median was found for each column. The median is that distance at which half the data points fall closer to the source and the other half farther away. As can be seen from the location of its plotted value on figure 2, it fell in the length in which the concentrations of data points were found. As noted above, a number of tabular displays similar to figure 2 were prepared. Each gave a pattern of scatter and of the location of the median at the point of data concentration, just as figure 2 does. Because of their similarity, they are not presented here, only figure 2 being used to illustrate their nature. Instead, the medians from each were plotted on the bar chart, figure 3, for easy and convenient comparison. There is no marked or consistent difference in the lengths of any set of bars on the bar chart.

Finally, the data were subjected to statistical treatment. The average or mean reduced distance was calculated for each category along with the standard deviation of the mean, $\overline{\sigma}$. If other sets of data of the same type were collected and the same quantities calculated, in about two out of three cases the new mean value would be within $1\overline{\sigma}$ of the mean value given here. In about 95 out of 100 cases, they would be no more than $2\overline{\sigma}$ from the value here given. The chances are about 370:1 that they would come within $3\overline{\sigma}$.

These data are compiled in Table 1, column 1 and 2, with $\overline{\sigma}$ given also as a percentage of $\overline{\lambda}$ in column 3. The exclusion of data indicated in the table in column 5 was done by the application of Chauvenet's criterion for the exclusion of an item from a set on the basis that, in comparison with the other items, it exerts undue influence on the mean values.[16] Finally, the ratio of the average λ for barricaded and unbarricaded conditions is given, along with the standard deviation of this ratio (columns 6 and 7). The results of this statistical treatment confirm the conclusions drawn from the visual presentation of the graph and bar chart. We see no difference between barricaded and unbarricaded conditions for the most part. In two categories, B and D, where substantial differences do occur, they show that the presence of barricades had an unfavorable effect.

The effect on the results of this study of placing individual damage items in wrong categories is of interest. In fact, it can be shown that this can have little effect on the overall result. If a substantial amount of category B barricaded data, say, mistakenly appears in the A category, the larger B distances would make the A barricaded category look very good compared to the A unbarricaded category. But one would expect on a random basis that some category A data would be getting into the B category at the same time and thus

---

[16] See reference on page 56.

25

Table 1. Statistical Summary

Categories		$\bar{\lambda}$	$\bar{\sigma}$	$\bar{\sigma}/\bar{\lambda}$, percent	Number of data points	Data points excluded	b/u[#]	$\bar{\sigma}_b/\bar{\sigma}_u$ percent
A	b	7.3	0.7	9.6	43	2		
	u	7.6	0.8	10.5	16	4		
	ratios						0.96	14.3
B	b	17.3	1.1	6.4	87	3		
	u	14.3	1.4	9.8	27	3		
	ratios						1.22	11.7
C	b	25.1	1.1	4.4	97	4		
	u	24.7	2.3	9.3	24	2		
	ratios						1.02	10.3
D	b	29.4	1.2	4.1	94	0		
	u	24.1	1.5	6.2	30	4		
	ratios						1.22	7.5
E	b	42.5	1.3	3.1	124	0		
	u	43.6	4.0	9.2	20	0		
	ratios						0.97	9.7
M	b	81.2	10.3	12.7	18	3		
	u	74.1	7.2	9.7	23	4		
	bd*	75.3	6.7	8.9	20	4		
	b:u						1.10	16.0
	b:bd						1.08	15.5

*barricade destroyed

[#]using $\bar{\lambda}$ values from column 2; average for categories A through E = 1.11

make the B barricaded category look worse than the B unbarricaded. However, unless very large samples are involved, cancellation of effects of erroneous data will not necessarily occur.

An illustration of this is apparent in the actual data for categories C and D unbarricaded. Here, one sees an apparent reversal in the distance (although the effect is not great enough to reverse the overall results regarding barricading). The $\bar{\sigma}$ values are, of course, more than adequately large to cover such a discrepancy. Yet the fact that reversal happened at all illustrates the variations in reporting damage.
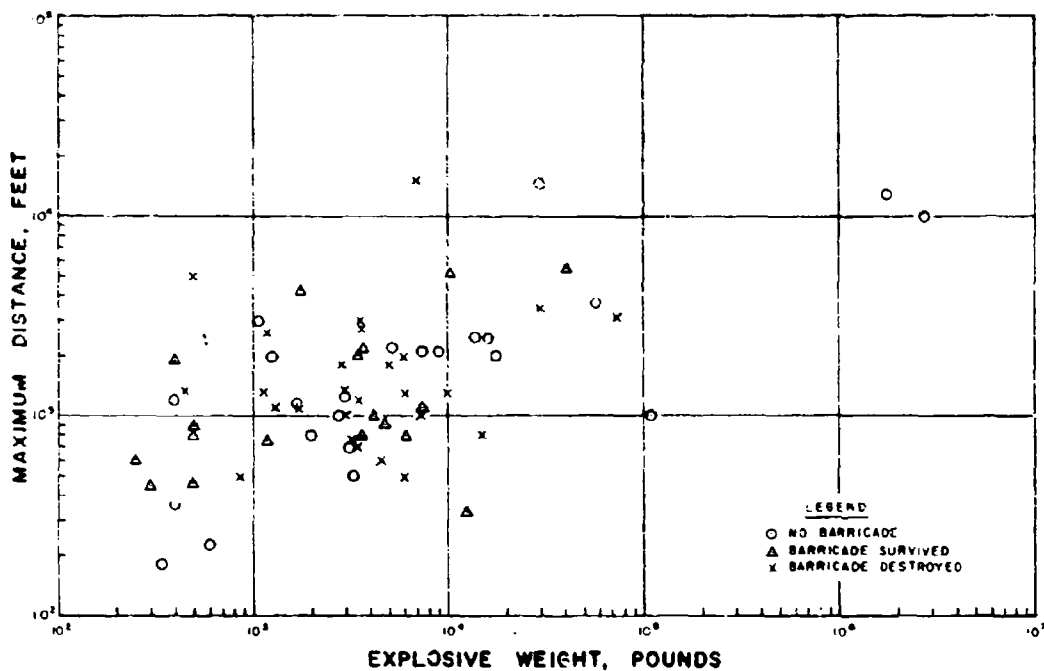
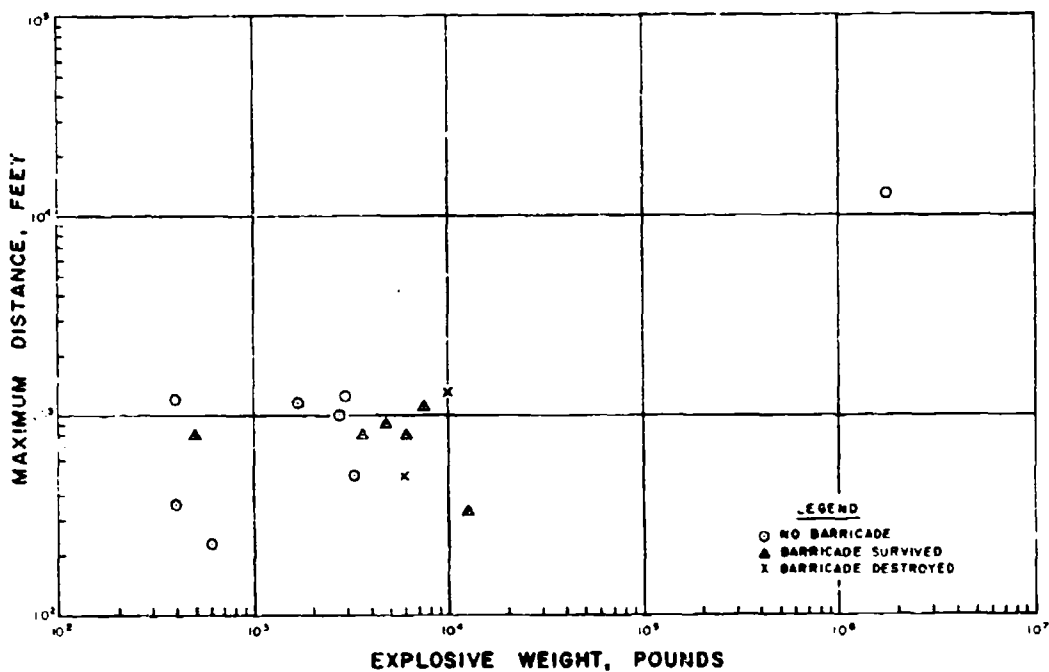Figure 4. Explosive weight vs maximum fragment distance.

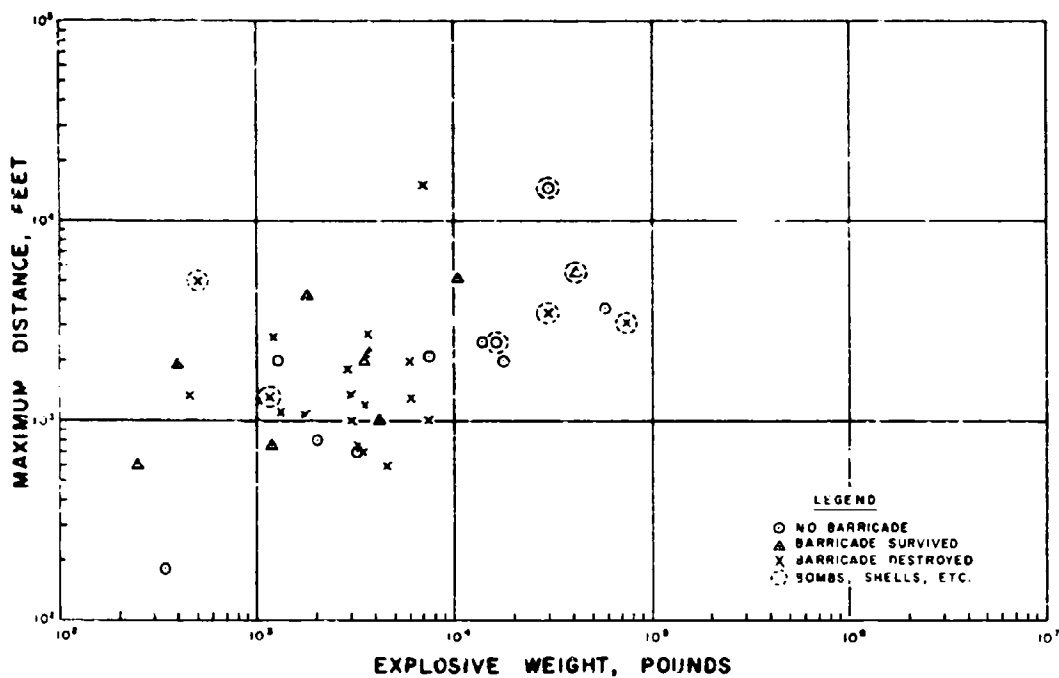
Figure 5. Maximum fragment distance, black powder.

27

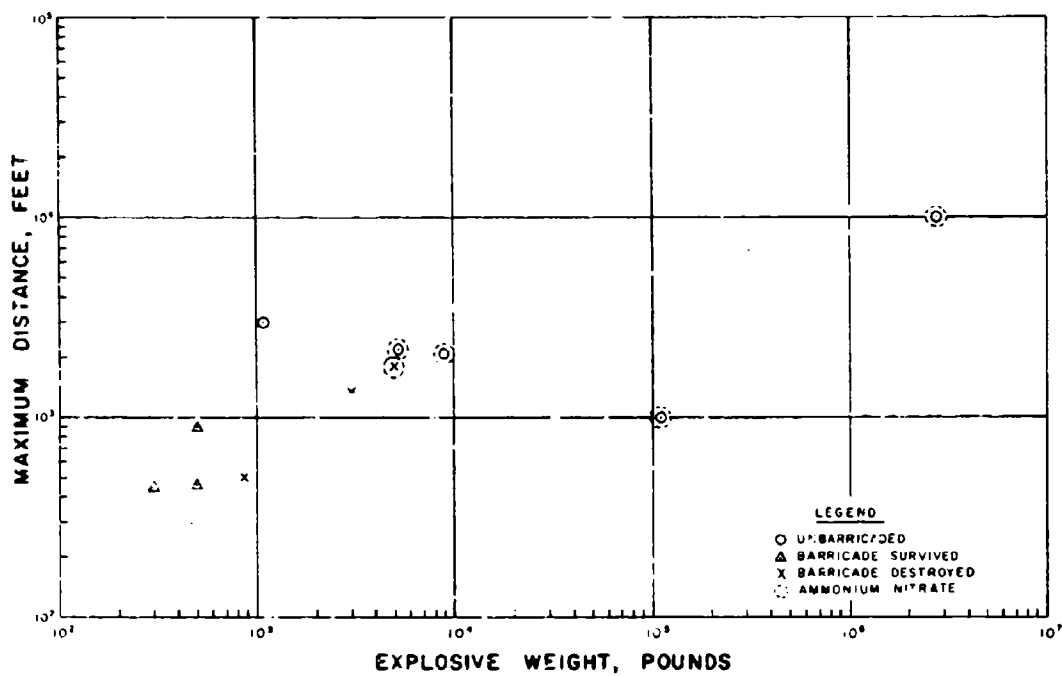Figure 6. Maximum fragment distance, high explosives.

Figure 7. Maximum fragment distance, ammonium nitrate and propellant.

28

However, while such uncertainties can and in this case did affect the results in connection with two adjacent categories, in a very minor way, the entire five categories could not be so affected in a consistent direction unless a bias were involved in the reporting of all damage categories, a circumstance that is not very likely.

In an attempt to produce an overall evaluation, all the data in all categories was used to get an average value for the barricaded and unbarricaded items. A ratio was then obtained as shown in the note to Table 1. This came out to be unfavorable to the use of barricades to the extent that the barricaded distance to some average level of damage is about 11% greater than the unbarricaded distance.

In a brief summary of this section, we may say that in no damage category is there support for halving distance for barricaded facilities. Indeed, there is no clear distinction at all apparent between barricaded and unbarricaded circumstances. Surprisingly, there is some indication that barricades increase the damage distance over unbarricaded circumstances.

MAXIMUM FRAGMENT DISTANCE

The next relationship considered was the maximum distance to which fragments were thrown. Data on this appear to be objective and in absolute quantities, reported with equal accuracy in all cases. Obviously, it is not a governing safety criterion.

In figure 4, points indicating the maximum distance at which fragments were found are plotted against explosive weight in pounds. Each point is coded to indicate whether the source was unbarricaded or if barricaded whether the barricade survived or was destroyed, by the use of appropriate symbols. Other plots were then extracted from this, each containing only points from accidents involving explosives of certain types. In figure 5, all points represent black powder explosions; figure 6, high explosives (with those contained in bombs coded); and figure 7, ammonium nitrate and propellants. These groupings are not intended to imply similarities or differences between the explosives in a group but only to permit a readable plot with the explosive identified for each point. Figure 4 was found to consist of uniformly scattered points with no clear trend apparent. If any trend could be assigned to such a plot, it might be that distance seems to increase at some power lower than the cube root of explosive weight, but even that statement cannot be defended.

29

The plots in figures 5 through 7 were prepared to find whether the scatter in figure 4 would be reduced if each type of explosive was considered separately. It might be reasonable to expect the type of explosive to affect the maximum fragment distance, on the basis that the fragment in contact with the explosive and accelerated to the particle velocity of the detonation wave would travel faster than any other. The particle velocity is determined by the type of explosive, and therefore so should the maximum fragment distance be.

From an examination of these plots, there appears to be a relationship between maximum fragment distance and explosive type, in that the high explosives (HE), and bombs in particular, give generally larger distances than the slower-burning materials. However, this difference between the types is more pronounced for larger quantities because the HE data appears to increase more with weight than the slower-burning materials. The lesser increase in distance with weight in low explosives is consistent with their tendency to incomplete, or at least nonsimultaneous, explosion. In view of this, it might be concluded from the data that maximum distance is a function of the total quantity likely to react simultaneously and that the type of explosive is important only in its effect on the probability of mass detonation.

The separation of data on the basis of type of explosive does definitely change its appearance and the inferences to be drawn from it. In particular, inferences concerning the choice of a reasonable upper bound for the distance would change, and this is the sort of inference upon which quantity-distance tables are based. In figure 4, for example, including all but a few points, one might choose a distance of 6,000 feet for charge weights up to 100,000 pounds as a reasonable protective distance. From figure 5, a constant value of perhaps 1,300 feet would be chosen for the same range. From figure 6, one could choose either a constant value of 6,000 feet for unlimited quantities of explosives, or a value like $300W^{1/3}$. From figure 7, one would arrive at a value of $50W^{1/3}$. Each of these choices would appear to have some justification, but each would be based upon a different category of explosive. With regard to figure 7, one would be using a different explosive for each end of a fitted curve.

With respect to the effectiveness of barricades, consideration either of the absence of the barricade or of its survival would not appear to shift the position of the upper bound on any of the plots in any consistent way. From figure 4, the unbarricaded cases appear to be bounded by 4,000 feet and the barricaded by 6,000 feet, approximately, up to 100,000 pounds. In figure 6, it appears to be about $250W^{1/3}$ for the unbarricaded cases against $300W^{1/3}$ for all of
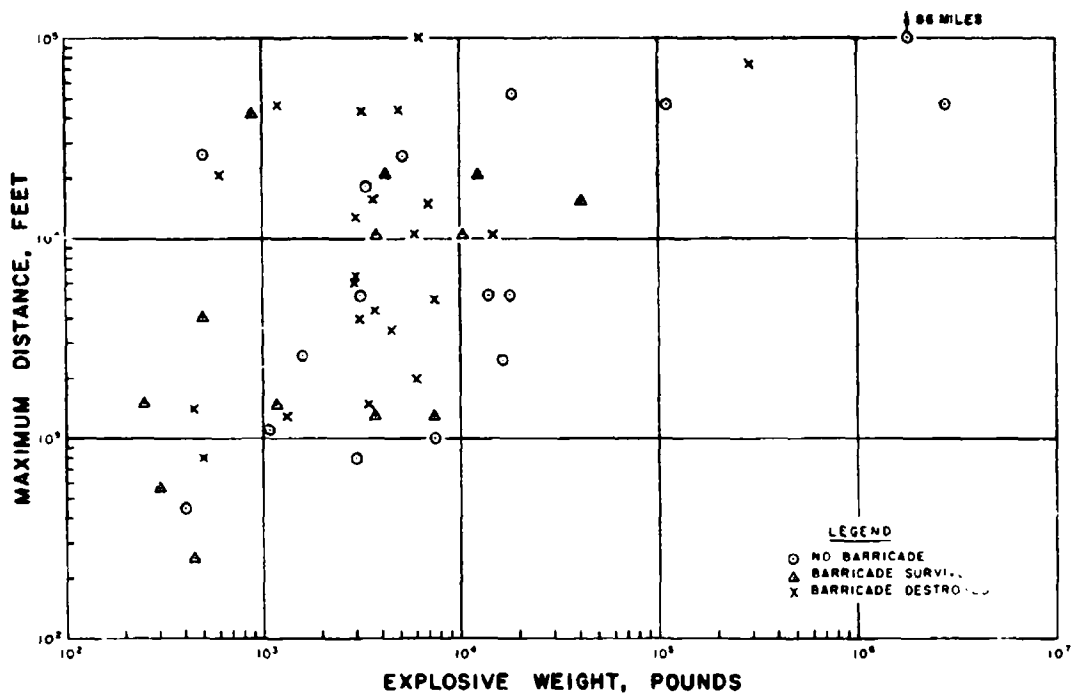
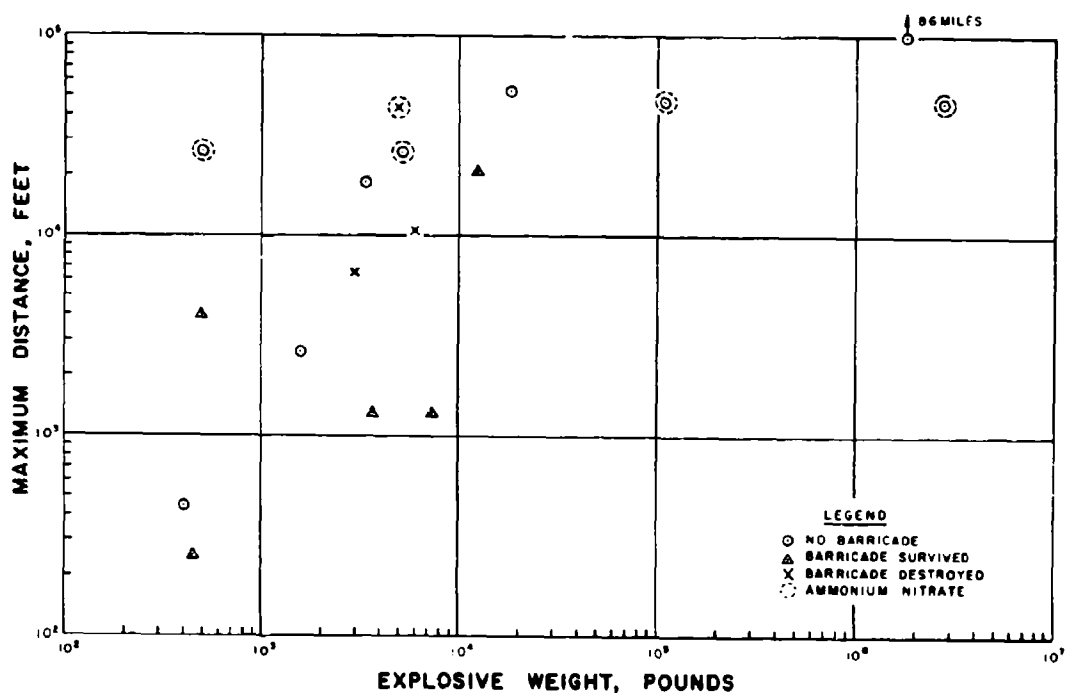Figure 8.   Maximum distance of glass breakage.

Figure 9.   Maximum distance of glass breakage:
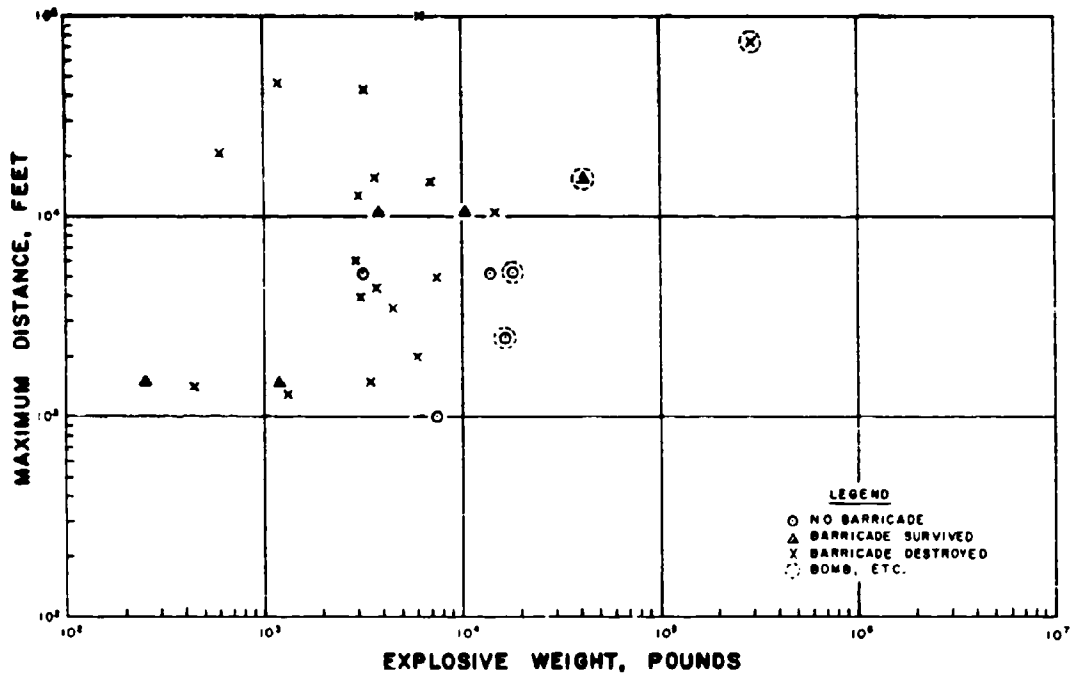black powder and ammonium nitrate.

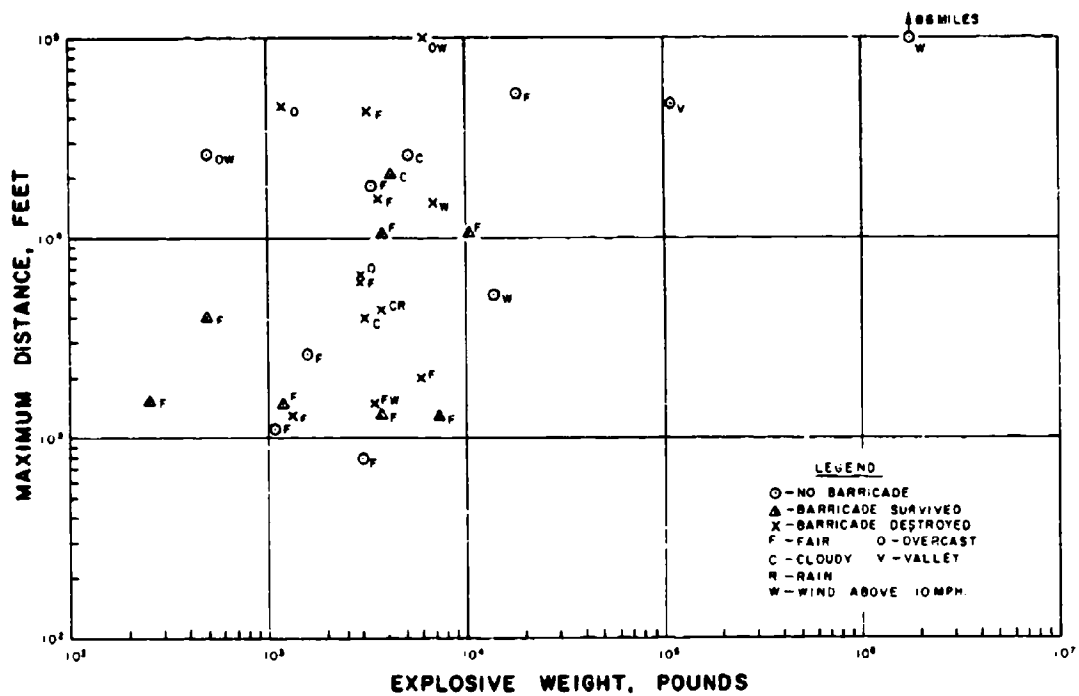Figure 10. Maximum distance of glass breakage: high explosives and bombs.

Figure 11. Maximum distance of glass breakage: weather conditions indicated.

the barricaded ones. Figures 5 and 7, on the other hand, appear to indicate that the upper bound is smaller in the barricaded cases. From all of this, one can reasonably conclude either that barricades have no effect on the maximum fragment distance, compared to explosive type, or that other parameters are not considered, or that the data available is too inconsistent for anyone to derive a conclusion from it.

In order to provide a more substantial basis for the barricade comparison, this data was treated statistically as in the preceding damage category study. For each item, the distance was divided by the cube root of the weight. The values for reduced distance (λ) were then averaged, the standard deviations calculated, and ratios formed for the barricaded-to-unbarricaded and barricaded-to-barricade-destroyed averages. These results are given in Table 1 in the M category. In this case, the results show the barricaded cases giving about a 10% greater distance than unbarricaded--a result not only consistent with but in remarkably close agreement with the overall result for the building damage study.

MAXIMUM DISTANCE OF GLASS BREAKAGE

In figure 8, points indicating the maximum distance at which glass breakage was reported are plotted against explosive weight. As in figure 4, each point is coded to indicate the barricade condition. In figures 9 and 10, the points are again extracted to identify certain types of explosives. In figure 11, only those points are plotted for which the weather was known, and each is coded accordingly.

The phenomenon involved here is actually the distance at which a few unusually weak or large windows existed. These could be broken by a low blast pressure, little stronger than the usual high winds in the area. Also, one should expect the distance to be affected by the terrain and climate on the whole path, rather than by the early high-pressure phase close to the explosion, as the fragment distance would be.

All of the data available was plotted on figure 8. From the figure, a lower bound at about $60W^{1/3}$ appears to be appropriate for data representing either the absence of a barricade or the presence of one that had survived. In cases in which the barricade was destroyed, however, the distance is twice as great, or approximately $120W^{1/3}$. The trend for the maximum distance appears to be similar, being $600W^{1/3}$ for the barricade-destroyed cases but approximately $300W^{1/3}$ for the others. Near the upper bound the points are much

33

fewer and the trend cannot be so well supported, although it may be estimated to be present from visual inspection.

A comment should be made on the possibility that earth shock had some effect on the results. Thus, the fact that a barricade survived may not have been the result of its having had greater strength but of the explosion having occurred farther above ground level. The explosions in which the barricade was flattened should be expected to have produced a much stronger earth shock, capable of cracking plaster or breaking windows at great distances. The fact that the greatest distance of glass breakage may be a result of ground shock rather than air blast may explain the fact that there appear to be two groupings to the data. In the upper group, there are fewer cases where the barricade survived, which could be interpreted to mean that these are mainly cases in which the explosion occurred near ground level, so the group represents the effects of ground shock. In the lower group, there are fewer cases of deep explosions, and results are more representative of air blasts. To accept such an explanation, however, one would need to assume that earth shock can break windows at greater distances than air blast.

From the data on the maximum distance of glass breakage as now plotted, the conclusion might be drawn that barricades have a negligible effect when they survive, but they significantly increase the radius of damage when destroyed by the blast. The mechanism responsible for this increase may be an augmentation of either the air or ground shock, at lesser or greater distances, respectively.

Before any conclusion can be accepted, however, two other conditions must be considered. One of these is the type of explosive and the other, the weather.

Figures 9 and 10 contain the same data as figure 8, but plotted separately to indicate explosive type. From these plots, it can be seen that the apparent relationships previously discussed have changed. For ammonium nitrate shots, figure 9, the maximum distance of breakage appears to be a constant and to be totally unrelated to charge weight. For bombs, figure 10, the distance appears to be a linear function of charge weight but to a slightly higher power, say 1.3, for black powder explosions. For the high explosives, such as nitroglycerin, all points appear to lie in a nearly vertical band, from which one might deduce that the maximum distance of glass breakage is either independent of charge weight or a function of charge weight to some power greater than W^2. These results indicate that the controlling parameter has not yet been introduced on the plot and that no conclusions can be reached from it.

In figure 11 the data from figure 8 was again plotted and was coded only for cases in which weather conditions were noted. From this, it is at once apparent that in all cases in which weather data was available, the weather was always fair when the breakage distance was less than 4,000 feet. When the distances were greater, cloudy or overcast conditions existed in nearly half of the cases. Further, although it does not show on the plot, many of the fair-weather situations at further than 4,000 feet appeared to be at times and in locations where inversions or other conditions would cause unusual propagation, according to the original records. For example, the 86-mile distance was across a lake, downwind.

The one result apparent from a study of figure 8 is that the presence of barricades, whether they survived or not, did not seem to influence the distance at which glass was broken. The lower bounds, discussed earlier as relationships of distance and charge weight, actually seem to be effects principally of weather, and partly of explosive type. For example, one might base a conclusion on the set of fair-weather shots. In this set, it would appear that the maximum distance was nearly a constant of about 2,000 feet, independent of charge weight or nearly so. However, when atmospheric layers or terrain features are present, these distances increase. Also, those in this set and above 1,000 feet were mostly sensitive high explosives which can be reliably depended on to detonate in mass and with high velocity. In other words, it appear that all anomalies and relationships can be explained without reference to the presence of barricades. It is therefore concluded that the presence of barricades has a negligible effect on the distance of glass breakage.

DISTANCE TO COMPARABLE STRUCTURAL DAMAGE, SELECTED CASES

In figures 12, 13, and 14, certain data was plotted in a manner intended to indicate whether source barricades caused a certain blast pressure to occur at a distance different from that at which it occurs in a similar explosion without a barricade. Using the 86 selected cases, figure 12 represents those with an unbarricaded source, figure 13 the barricade-survived cases, and figure 14 the barricade-destroyed. It was intended to bound the distance at which a blast pressure of a certain level occurred, the chosen level being that which was just enough to cause damage to wall studs or rafters in an ordinary frame building. The nearest building damaged at least this badly is indicated on each plot by an X if it was itself unbarricaded and by a * if it was barricaded. The nearest building with damage of a lower level is indicated by an open circle if unbarricaded, by a filled-in circle if there was a barricade around it.

Data points from the same explosion are joined by lines par-
lell to the distance a..is. Ideally, these vertical lines should
form a band across the plot, within which a curve could be drawn
identifying the distance to a certain pressure for explosions of
any weight. Also ideally, each vertical line should have a damaged
building at its lower end and an undamaged building at its upper
end. However, the opposite often occurs because of the variability
in strength of buildings and the fact that each was chosen according
to its own damage level rather than pairs being selected. From the
nature of the cube-root scaling law that applies, the curves should
appear as straight lines with a slope of 1/3 on the full logarithmic
scales used. Actually, however, two lines might be required on each
plot, one referring to buildings in which the damage level is deter-
mined by the peak blast pressure, the other by total impulse. Since
the scaling relationship for each involves the explosive weight,
however, and in view of the physical situation involved, there is
no reason to expect both lines not to lie within any band defined
by data of the kind available.

Except for the unbarricaded plot, figure 12, the pattern of
the data points does not encourage drawing lines to define or bound
the band concerned. For purposes of discussion, bounding lines were
fitted to figure 12 and then the same lines were drawn on each of
the others. In the plot for unbarricaded cases, it appears that
$43W^{1/3}$ serves as an upper bound and $15W^{1/3}$, a lower bound. From
air blast tables,[15] these values identify a band of pressure from
0.9 to 3.2 pound per square inch (psi), a reasonable range for the
low level of damage to weak buildings. It will be observed that
only three damaged buildings are above this band and only four less-
damaged ones, below it. Alternately, one may consider the upper
bound as that distance beyond which few buildings suffer as much
damage as broken rafters, and the lower bound the distance within
which few buildings are less damaged.

When the bounds from figure 12 were plotted on figure 13, they
did not appear to fit so well. A rather large number of points
fell outside of the band, and the number of more-damaged buildings
above it and less-damaged buildings below it both increased. To
enclose an equivalent proportion of points, it would be necessary
to raise the upper bound to approximately $54W^{1/3}$ and to reduce the
lower bound to approximately $11W^{1/3}$. With this band, the number of
more-damaged buildings above it would still be four, while the number
of undamaged structures below it would also be five, but three of
these would be themselves barricaded.
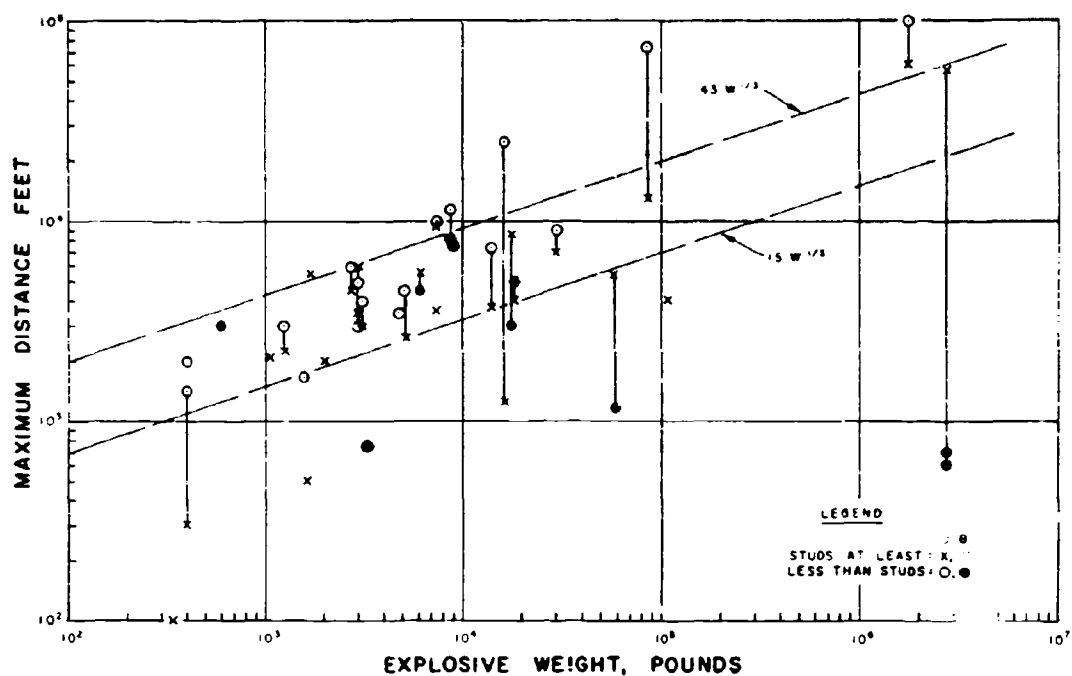
---

[15]See reference on page 56.

36

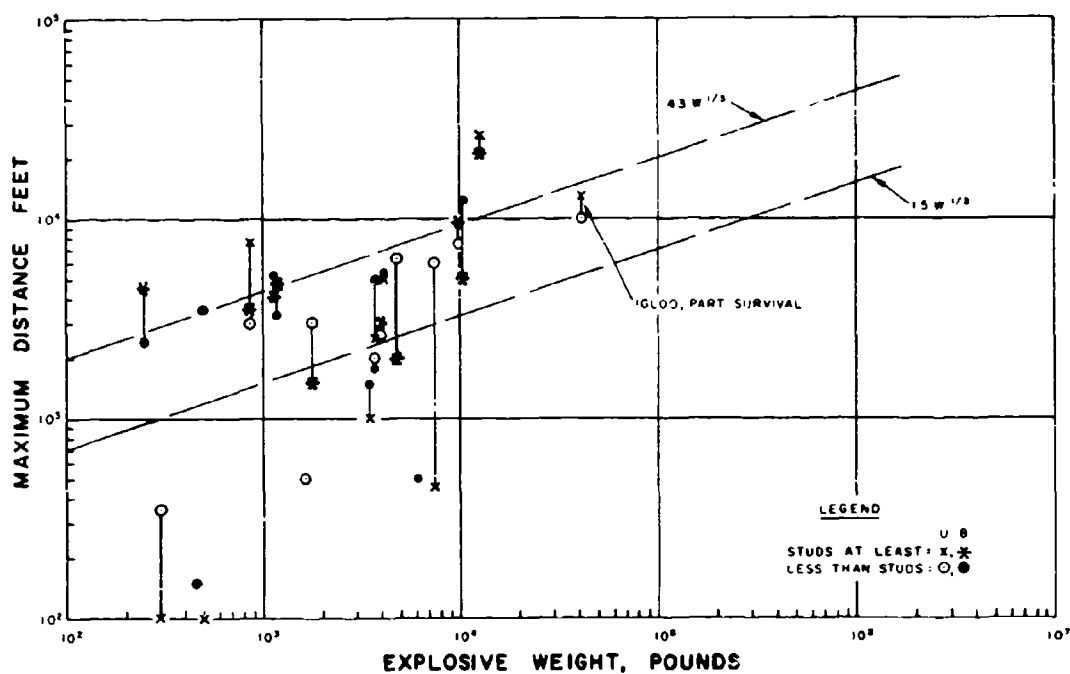Figure 12. Structural damage, unbarricaded source.

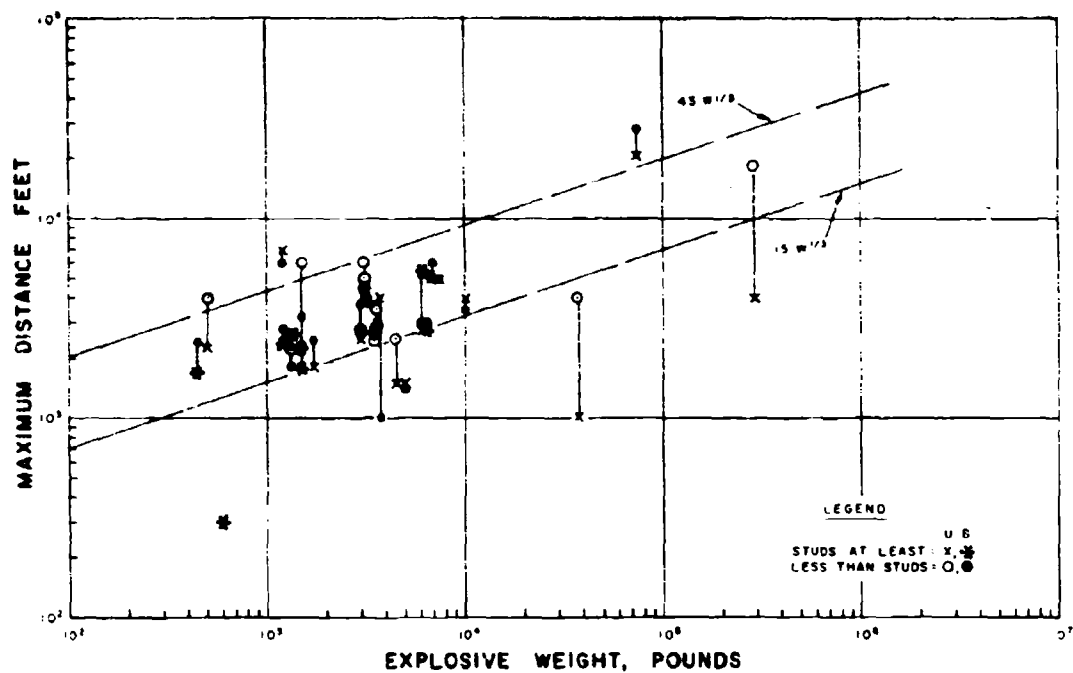Figure 13. Structural damage, source barricade survived.

Figure 14. Structural damage, source barricade, destroyed.

As a means of clarifying this problem, the type of explosive involved in each data point was considered. It was found that all of the points lying below 100 feet and three points at 200 feet represented materials other than high explosives, that is, black powder or similar materials which cannot be relied upon to detonate simultaneously. If all but high explosive points are neglected, the $15W^{1/3}$ line is above all but three points, of which only one is a less-damaged building, and all three lie above 100 feet. After this had been done, the band from $15W^{1/3}$ to $54W^{1/3}$ appeared satisfactory for figure 13 except for the larger number of more-damaged buildings above it, as the $15W^{1/3}$ to $43W^{1/3}$ lines had for figure 12. A check of weather and other conditions produced no information concerning these points except that two of them represented black powder and one was rocket propellant. If one considers the slow-burning characteristics of these materials as being capable of producing a blast wave more like a very high wind, the points can be explained. Such a wind might not attenuate with the square root of distance like a true blast wave and, with its long duration, could still possess an impulse capable of causing damage of the level considered. On this basis, figure 13 is well fitted by the $15W^{1/3}$ and $54W^{1/3}$ bounds.

When these same bounds are plotted on figure 14, they appear to fit reasonably well. The majority of data points are contained between them, and the numbers of damaged and undamaged buildings above and below the bound, respectively, are comparable. The upper bound could be lowered to perhaps $34 W^{1/3}$ before the number of damaged buildings above it exceeded two, and without a significant increase in the number of points outside it. However, any raising of the lower bound would cause a large increase in the number of excluded data points, particularly for less-damaged structures. There are already four less-damaged structures below the lower bound, of which three are themselves barricaded. In general, the bounds of $15W^{1/3}$ and $43W^{1/3}$ appear to fit the data points as well as, or better than, any others that might be chosen.

Here again we find that, within the limitations of this study, no reasonable distinction can be observed between barricaded and unbarricaded cases.

RESULTS OF DATA STUDIES

Throughout each of the data studies, care was taken to pursue each application and investigation of the data independently of others so that each would be internally consistent and unbiased by other results to the greatest extent possible. At this point, it is appropriate to compare the different findings from the separate approaches and to evaluate the significance to the overall problem of those things on which agreement was found.

BARRICADE EFFECTIVENESS

The most consistent finding was that related to the effective-
ness of barricades. From each of the several ways in which the data
was organized and analyzed, nothing was found to indicate that bar-
ricades provided protection from an explosion or significantly
influenced any of the effects that were studied. This was a consis-
tent result of every approach used. Their presence did not affect
the distance at which various categories of structural damage
occurred, the distance at which a certain level of structural damage
corresponding to a certain blast pressure occurred, the maximum
distance to which fragments were thrown, or the maximum distance at
which glass was broken.

This finding on the effectiveness of barricades applies fully
only to protection from the effects actually studied. It should be
noted that these do not include all of the effects of explosions for
which barricades are generally considered to provide protection.
A particular example of such an effect is that the probability of
propagation of an incident to explosives at other locations by
primary fragments may be reduced if they are intercepted by the
barricade and significantly reduced in velocity. However, the extent
of explosion damage to the barricade itself revealed by this study
raises a question regarding the role of barricade debris as a source
of hazards.

Admittedly, the data considered had all of the scatter and error
inherent in data of this sort. Yet it is the opinion of those who
performed the study that so great a mass of data on the results of
accidental explosions has never before been collected and analyzed.
Although the scatter of the data is sufficient to conceal some
difference in each effect as a result of the presence of barricades,
certainly it is not so great that it could obscure a protective
value of barricades that would justify the application of the bar-
ricaded half-distance rule. The difference that could be concealed
by scatter is not nearly that much and would appear to be little more
than 10% of the distance in any case. In fact, rather than indicating
that barricades provided protection, where there seemed to be any
difference the data tended to indicate that the damage was worse
when barricades were present. Such differences in some cases were
large enough to have statistical validity.

The finding that barricades at the source may increase certain
types of damage is consistent with the results of some other studies.
Recent controlled experiments by the British have indicated that
barricades increase the damage radius.[11] If such a result appears

---

[11]See reference on page 55.

40

unreasonable, it should be noted that there is evidence to the effect
that, although a certain amount of the energy of an explosion is
permanently acquired by confining materials, inclosing a chemical
explosive with an inert mass of material may serve to increase the
total energy released and also th. energy in the blast wave. This
may result from the inertia of th confining materials and the con-
sequently increased time availab' after detonation for energy-
increasing chemical processes. 1 some excellently documented con-
trolled experiments, cased char 's and confined explosions in general
have been shown to produce enha ed blast effects.[17][18] A similar
result has also been observed r..ently in large scale dividing wall
tests.[20]

"SAFE" DISTANCES

Building collapse, according to extensive British and America
studies of bomb damage in World War II,[13][14] is significant out to
a blast pressure of 2 psi ($\lambda = 28$). From this distance out to the
limit of glass breakage, the lesser hazards drop in a gradual manner
to zero. Injury to individuals caused directly by blast pressure
does not occur at this range but they may be injured by flying debris.
The closer the building is to the blast, the greater the amount and
velocity of the debris and the greater the potential for injury or
death.

Figure 2 shows clearly that most damage out to the D, or slight,
category occurs within a reduced distance of 40 regardless of the
presence or absence of barricades. This fact helps to explain the
historical success of the ATD. The present Department of Defense
standards for barricaded inhabited buildings permit an exposure in
the most extreme case roughly equivalent to a reduced distance of 40
(1.3 to 1.4 psi). It is clear that actual experience as evidenced
by our data shows this distance to be reasonable even if the building
is unbarricaded. For the Department of Defense unbarricaded distance,
our data shows nearly all damage except that in the E, or minor,
category would be avoided.

Stated another way, the results of our study indicate that the
effectiveness of the inhabited building distance tables has nothing
to do with barricades but rather, that the distances used in most
cases are in fact reasonable.

---

[13][14][17][18][20] See references on page 56.

QUANTITY-DISTANCE RELATIONSHIPS

The studies of building damage in the more severe categories strongly support the cube-root scaling law, which states that explosions of different weight produce comparable effects at equal reduced distances. This scaling relationship was not so obvious for instances of less severe damage or maximum fragment travel, where other factors such as the weather and the type of explosive appear to affect the result. The other factors are discussed in a subsequent section. Here, the intent is to establish the range and damage levels in which the other factors do not appear importantly to affect the scaling laws.

In some of the studies, data was plotted on the basis of reduced distance (figure 2 and 3), while in others (figures 12, 13, and 14), curves plotted as functions of the cube root of explosive weight were found to fit data plotted on an actual distance basis. In the first case, all buildings about which sufficient information was available were plotted according to categories of damage, each being placed in a distinct category according to precise definitions of the corresponding level of building damage. In the other case, only those buildings that had an identical level of damage, or slightly more or less, were plotted. According to the defined categories of damage level in the first case, the damage level considered in the second category fell at the border between category C, moderate damage, and category D, slight damage. From the second study, the data points were found effectively enclosed within a band between the scaled distances of 15 and 43. A study of the graphical display produced in the first study indicates that this range encompasses the great majority of buildings in categories C and D, whose medians lie near 25. On the other hand, the median for category B lies near 15, excluding half of its points, while nearly half of category E is excluded by its median falling near 43. Considering the narrow change in damage used to distinguish categories, the agreement is fairly good.

OTHER FACTORS

As mentioned earlier, there are certain effects which do not appear to demonstrate the scaling relationships. These are explosion effects at long distances and of small importance, such as glass breakage and the maximum distance to which fragments are thrown. The factors involved are summarized in the following discussion.

The maximum distance to which fragments were thrown appeared to be dependent on the total weight of explosive to only a limited

extent, certainly not by a simple cube-root law. Its relationship
to the quantity appeared to involve the type of explosive in terms
of the quantity likely to detonate simultaneously. One should not
expect it to scale as well with the explosive weight as the air
blast does because the energy acquired by a fragment is not a simple
function of the total explosive weight. It need acquire only enough
momentum to leave the explosive environment. During this process,
some of the energy furnished to it must be used to break its bonds
with earth, a process which may or may not use a significant portion.
After leaving the explosive environment, the drag on it is a function
of its velocity, so that it will slow more rapidly in the early parts
of its flight. Considering the extremely high drag at early stages
of flight, it is possible that there is a maximum distance beyond
which no irregularly shaped fragment can be thrown, no matter how
great the explosion, because all could slow to some equal velocity
within a short distance. Considered in terms of the factors in-
volved, the findings of the maximum fragment distance should not be
considered invalid for the simple reason that no scaling law is
demonstrated.

Similarly, the failure to demonstrate a scaling relationship
snould not cause one to reject the validity of results from the
building damage of negligible importance, such as glass breakage.
Early in the study, the rate of change in blast pressure with
distance and the variations in structures was described as causing
great scatter. In addition, the work on the maximum distance of
glass breakage showed great effects of weather and of the type of
explosive. It is significant that the effects changed by weather
were limited to these caused by a blast pressure of less than 1 psi.
From this, one can estimate with some confidence the strongest blast
wave that can be deflected or focused by a normal atmospheric dis-
continuity, and thus the blast level below which distances cannot be
well predicted. Fortunately, it appears that blast effects do not
become unpredictable because of these other factors until below that
level from which protection is normally felt to be necessary.

CONCLUSIONS

1. A comprehensive examination of all available accident reports
revealed no evidence that barricades affect the extent of damage to
structures in their vicinity.

2. A thorough review of the literature revealed that American
practice with respect to barricades is heavily influenced by a single
report, published 56 years ago, whose primary and apparently achieved
goal was to establish safe inhabited building distances. This report

43

arbitrarily introduced the practice of doubling the inhabited building distances when barricades are not used but did not provide any information by way of justification for, or comment on, this practice, or for that matter, the use of barricades in general.

3. Several more recent studies based on accident data and an experimental study of the effects of barricades on blast pressure showed no effect of barricades in reducing either the damage or the blast pressure at inhabited building distances.

4. From a study of the types of data available in records of accidental explosions, it does not seem possible to use such data to evaluate quantitatively the effectiveness of barricades on a general basis in influencing certain phenomena of explosions. This is particularly true of close-in effects, such as dense fragment patterns, even if data were available from a large number of both barricaded and unbarricaded explosions.

5. Barricades are themselves destroyed by explosions involving quantities of explosives that are relatively small compared with the full weight of the explosive against which the type of barricade is used to furnish protection.

6. Although the development of quantity-distance relationships was not a purpose of the study, the results of this study lead naturally to the conclusion that in certain instances the quantity-distance tables provide the intended level of protection at the distances prescribed for inhabited buildings in a barricaded arrangement, whether barricades are present or not.

7. Within the accuracy that the data permitted, significant building damage appeared to be related to distance and explosive weight in accordance with the cube-root scaling law in the same manner as blast pressure, regardless of the presence of barricades.

8. The maximum distance to which fragments are thrown did not appear to scale according to the cube-root law or to be affected by the presence of barricades.

9. The maximum distance to which very minor damage, such as glass breakage, occurred to buildings does not depend on the presence of barricades and does not scale with explosive weight according to the cube-root scaling law but, instead, is greatly affected by weather and by the type of explosive; for example, high explosives or black powder.

44

RECOMMENDATIONS

COMMENT

In the course of obtaining the information needed for the purpose intended by the directive that established the study team, certain opinions were formed that have little direct relationship to that precise purpose. In the belief that these opinions will assist the reader in understanding the basic report, the team presents them here in the form of recommendations with brief clarifying discussions.

PROTECTION AT INHABITED BUILDING DISTANCE AND BEYOND

Recommendation

> To assist in solving design problems, it is recommended that existing quantity-distance tables be supplemented with blast and impulse scaling relationships.

Discussion

This study has confirmed the findings of earlier studies that distance itself furnishes a predictable level of protection for ordinary structures against blast damage whether barricades are present or not. It can be reasoned that building damage is related to blast pressure, which can be predicted at any specified distance from the potential source of explosion, except for such minor damage as glass breakage, whose radius is affected by weather and other factors. If the designer were furnished with values for the blast pressure and impulse that could occur at a given location, he could design a structure which at that site would suffer damage only to some minimal or acceptable level. In many cases, this could be done by orienting and sizing minor features such as windows and doors. Extraordinary construction of this sort would be particularly appropriate for places of public assembly slightly beyond the inhabited building distances.

PROTECTION AT CLOSE DISTANCES

Recommendation

> A manual should be prepared that describes blast flow patterns and pressures to facilitate the design of structures which could be placed as close to the operation as needed

Discussion

Work processes sometimes make it necessary for personnel and valuable equipment to be located closer to the source of a possible explosion than the distance found safe in this study. Generally, personnel and equipment are safe at the barricaded inhabited building distance, but structures at closer distances are considered expendable. Current manuals contain little information on furnishing protection at these closer distances, except in cases where the quantity of explosives involved is very small. In some cases, there have been ill-advised attempts to use barricades as operational shields, in the sincere belief that they will furnish protection from fragments and blast pressures for persons working behind them as well as for equipment and buildings. However, only the most limited technical information for design of such features is given in the manuals.

This study did not deal specifically with the problem of close-in hazards, but some opinions concerning them were formed. With regard to fragment hazards, the fact that barricades have no effect on long-distance fragment travel implies that the pattern or trajectory of high-angle fragments does not change, either at great distances or close-in. At the closer distance, however, a barricade is intended to furnish some protection from low-angle, high-velocity fragments. The damage to barricades by even rather small explosions raises serious questions in this regard. The material torn from barricades, even when the bulk remained standing, appeared to spread over the area rather than merely move a short distance. Some of this debris, at least, appears as rather high-velocity fragments, and the total number of fragments is probably increased. This effect is recognized in the standard specifications for building earth-filled barricades, which require that all gravel sizes be carefully controlled. In addition to concern as to the efficacy of barricades for reducing certain fragment hazards, their ability to protect from close-in, high-pressure blast is also a quality that would need to be established for each case. Because of the complexity of blast wave flow, blast pressures close-in cannot be predicted, at least not in general terms. However, such pressures are likely to be highly dependent on the geometry of the barricade. In summary, the protection furnished to close-in personnel or property by barricades or shields cannot be determined from the type of information available to this study nor from the current manuals.

An alternate proposal is to design all facilities that may be affected by explosions to withstand the predicted explosion effects, replacing the quantity-distance tables themselves with predicted values of the pressure and impulse of the blast and the size and velocity of fragments that are expected in a given accident. Then

46

the problem of protecting close-in personnel and property will merge
with that of providing protective shields, dividing walls, or barri-
cades. Much information on the design of protective structures for
high blast exposure has been developed in the program of research,
for example, into the means of hardening missile bases against
enemy attack.[19]

It is the opinion of the investigators that, with intelligent
use of that information and with a knowledge of the chemical pro-
cessing problems, an economical plant could be constructed for the
production of nitroglycerin and dynamite, as examples, in which no
workman need be killed, and in which damage would be limited to an
acceptable maximum in any accidental explosion. The preparation of
a manual serving as the foundation for such an approach and the use
of structures designed for a known level of protection are strongly
recommended. On the other hand, it has not been shown that barricades
at the source provide any measurable degree of protection, and their
use for this purpose is not recommended, nor can it be economically
justified.

OVERALL RECOMMENDATIONS

Recommendations

A manual on the effects of conventional explosions and
the means of designing against them should be prepared at an
early date.

Continued effort should be made to evaluate certain
other hazards, such as the pattern of close-in fragments
including fire-causing substances, and the means by which
a second store of explosives can be protected against
propagation when close to a first accidental explosion.

Discussion

Those who performed this study concluded that the general
system of providing safety in the construction of explosives facili-
ties fails seriously to take adequate advantage of available scientific
knowledge that could be applied to the problems. Manuals do not
contain descriptions of the effects of explosions and modes of
target structure failure which must be avoided, but they do contain
highly refined rules of thumb, which are sometimes inadequate as
engineering criteria. Continuing the accident studies on an

---

[19] See reference on page 56.

empirical basis and unrelated to physical analysis can only further
refine the rules of thumb, and it is not recommended. Past accidents
furnish much information on accident causes and the patterns of
failure of conventionally designed buildings but are severely limited
for purposes of evaluating other methods of reducing danger. Some
damage mechanisms cannot be evaluated from accident records at all.

ACKNOWLEDGMENTS

Completion of this study in its present form would not have been possible if a substantial amount of assistance had not been freely rendered by many organizations and individuals. While natural courtesy or a desire for benefit can inspire helpfulness, assistance of the magnitude experienced must have been more the result of a desire to protect workmen and to promote national defense. In part to reduce the workload imposed on the ASESB Staff and partly on Miss Beverly Mast, who so capably performed all clerical duties associated with this study, the names of only a few of the most helpful persons are listed below.

Mr. Henry Marsh of Wilmington, Delaware, Consultant

Mr. L. W. Greiner, Manager of Safety, Hercules Incorporated

Mr. J. W. Burkholder, Explosives Production Department,
Atlas Chemical Industries, Inc.

Mr. Stanley F. Spence, American Cyanamid Company

Mr. Donaldson, Director, Explosives Department; Mr. Wendell Jackson;
Dr. Clyde Davis; E. I. duPont deNemours & Company

Mr. H. L. Hampton, The Institute of Makers of Explosives

Col. Leland S. McCants, USAF; Col. Edward H. Hilsman, USA;
Mr. Russel G. Perkins, Mr. Robert C. Herman, and Mr. Charles A. Breeding,
the Staff of the Armed Services Explosives Safety Board

Lt. Col. Cavanaugh, Mr. Iversen, Mr. Roscoe Eichelberger,
Mr. Tyrus Vernon of the 2705th Airmunitions Wing, United States Air Force,
Hill AFB, Utah

Col. Joseph Patalive and Mr. D. E. Endsley, Deputy The Inspector
General for Inspection and Safety, Headquarters, United States Air Force
(AFIAS-G2), Norton AFB, California

Mr. F. M. Bishoff and Mr. L. Jezek, Army Materiel Command (AMCAD-S),
Washington, D.C.

Cdr. Boland, Chief, Investigations Division, Office of the Judge
Advocate General, Department of the Navy

49

ASSISTANT SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301

INSTALLATIONS AND LOGISTICS

IT

10 June 1964

MEMORANDUM FOR The Assistant Secretary of the Army (I&L)
              The Assistant Secretary of the Navy (I&L)
              The Assistant Secretary of the Air Force (I&L)

SUBJECT: Study of Barricade Effectiveness

Engineers and technicians associated with the analysis and design
of barricades to provide facilities protection from the effects of
explosions have expressed increasing concern relative to the ef-
fectiveness of barricades as a positive method of protection.
Limited scientific data, including high-speed motion picture se-
quences and test instrumentation, have indicated that a lesser degree
of protection may be afforded by the barricades than has been as-
sumed in the past. The economical considerations are the initial cost
and maintenance of barricades weighed against land acquisition, re-
strictive easements, and increased access and utilities. If in
fact, barricades are not adequately serving the intended purpose,
adjacent public properties and on-base facilities may be exposed to
serious damage and loss of life should an incident occur.

The views expressed above have prompted both the Board Members and
Technical Staff of the Armed Services Explosives Safety Board to
seek scientific data to determine the actual effectiveness of barri-
cades and the reliability of the assumed protection under the general
conditions encountered on military installations, ammunition depots,
and holding and shipping points. An initial step toward this ob-
jective is a thorough literature search, compilation and evaluation
of data pertaining to the subject, from reports of tests and inci-
dents currently available in both Government and industry. Data thus
collected must be evaluated by recognized experts in the explosives
field as to its significance and reliability, and the degree of con-
fidence which may or may not be placed in the current standards for
use of barricades. It is anticipated that further tests may
eventually be required in order to confirm or revise the standards
for the use of barricades, with a confidence level commensurate with
the economic and safety aspects of the problem.

A solution to the imponderables of the barricade question is both
a timely and urgent requirement. Accordingly, it is desired that each

51

Department detail for temporary duty with the Board one employee
having the technical qualifications required for the literature search
and evaluation outlined above. The individual selected must be ac-
ceptable to the Board Chairman, and must be made available for an
uninterrupted period of 90 days. Assignment should be from the Wash-
ington area, if possible. The Board will bear the costs of travel and
TDY which may be required outside the Washington area.

Inclusive dates of TDY should be arranged by direct contact with the
Chairman, Armed Services Explosives Safety Board.

THOMAS D. MORRIS
Assistant Secretary of Defense
Installations and Logistics

Copy for:
Chairman/ASESB

52

APPENDIX II

Extracts from House Document 199, 70th Congress*

Page 2

"5. ... As regards the 'safety' of individuals and
structures outside the boundaries of ammunition depots, the
word 'safety' is a relative term. No one is ever absolutely
safe from injury. The average chance of the average individual
of escaping injury has, by custom, been termed 'safe.' It is
with such an understanding that the Board uses the expression.

Page 3

"8. ...
            (e) ... A pile of such ammunition after burning for
a short time becomes a violent fire, fed by the smokeless
powder in the propelling charges and the wood of the packing
boxes. The projectiles explode one at a time as they become
heated. The maximum missile hazard is believed to be less
than 1,200 feet, but the Board has adopted 1,200 feet to be
entirely safe." (Underline supplied.)

Page 7

"23. ...
            (b). Storage of all types of material should be so
arranged as to reduce or limit the Government property loss
from fire or explosion. In the case of new facilities, a
definite risk limit has been set and followed in planning the
facilities. In the case of existing facilities and stores,
the storage at each depot should be so arranged as to hold
the loss at the minimum consistent with the quantity of
stores and the facilities available.

Page 44

"(b). Risk to life and limb. ...

As covering both of the above requirements, the following
is the definition for 'Substantial structural damage:
            (1) In stone or brick houses.
            The serious weakening of or displacement of portions of
supporting walls (i.e., foundations, side walls or interior

---

*U.S. House of Representatives. Ammunition Storage Conditions.
House Document No. 199. 70th Cong., 1st Sess., March 12, 1928.

supports) and the breaking of roof rafters or other important
roof supports or floor joists.
    (2) In frame buildings.
    The serious weakening of or displacement of foundations,
the breaking of any of the main supports in the side walls or
interior supporting walls, and the breaking of any main supports
of the roof or floors.
    In measuring area of damage, no distinction was made as
to whether the building involved was structurally strong or
the reverse, as much weight being given to a flimsy building
as to one of brick or stone, and the distances as prescribed
embrace the extreme cases of damage."

APPENDIX III

REFERENCES

1. Assheton, Ralph. History of Explosions. The Institute of Makers of Explosives. Wilmington: Privately printed, 1930.

2. The American Table of Distances. The Institute of Makers of Explosives. (Pamphlet 2 (Revised). New York, 30 September 1955.

3. Ordnance Safety Manual. Department of the Army (ORDM 7-224) (AMCR 385-224). Washington. D.C., 15 February 1961.

4. Ground Safety, Explosives Safety Manual. Department of the Air Force (AFM 127-100). Washington, D.C., 20 April 1964.

5. Ammunition Ashore, Production and Renovation. Department of the Navy, Bureau of Ordnance (OP 5, Vol 2). Washington, D.C., 1 August 1963.

6. The Blast Effects of the Explosion at South Amboy, New Jersey, on 19 May 1950. Department of Defense. Prepared by Air Force Special Weapons Command, Washington, D.C., 27 July 1950.

7. Walther, L.C. "Location and Type Construction for Personnel Shelters." Minutes of the Seventh Explosives Safety Seminar on High-Energy Propellants, p. 99-113. Armed Services Explosives Safety Board, Washington, D.C., 24-26 August 1965.

8. Robinson, Clark Shove. Explosions, Their Anatomy and Destructiveness. New York: McGraw-Hill Book Co., Inc., 1944.

9. Wollman, S. "Effects of Barricades on Limiting Distance for Material Damage." Department of the Navy, Bureau of Ordnance (Explosives Research Memorandum No. 14). Washington, D.C., 19 September 1944.

10. Ilsley, Ralph. "Reappraisal of the American Table of Distances, and Recommended Bases for Discussion, Modification, and Final Approval of Minimum Risk Distances, etc." Army-Navy Explosives Safety Board, Unpublished Paper, 1 July 1948.

11. Warren, A. "Distant Blast Pressures from Traversed and Untraversed Explosive Charges." Armament Research and Development Establishment (Report (MX) 20/58). Fort Halstead, Kent, England, July 1958.

55

12. Cook, Melvin A. The Science of High Explosives. New York: Reinhold Publishing Corporation, p. 2-3., 1958.

13. "Notes on the Basis of Outside Safety Distances for Explosives Involving the Risk of Mass Explosion." Interdepartmental Explosives Storage and Transport Committee of the United Kingdom (3/7/Explos/43). 1948.

14. Robinson, Clark Shove. "The Present Status of the American Table of Distance." Army-Navy Explosives Safety Board Technical Paper No. 1, p. 5. Washington, D.C., 1 July 1945.

15. Glasstone, Samuel (ed). The Effects of Nuclear Weapons. United States Atomic Energy Commission, Washington, D.C., April 1962.

16. Worthing, Archie G., and Gefner, Joseph. Treatment of Experimental Data. New York: John Wiley & Sons, Inc., 1955.

17. Pittman, J. "Close-in Air Blast Measurements from Explosions of Bare and Rubber Cased 473-gm Spherical Pentolite Charges." Department of the Navy, U.S. Naval Ordnance Laboratory (NavOrd Report 4472). White Oak, Md., April 1957.

18. Filler, W.S., Morris, W.E., Fisher, E.M. "Explosion Phenomena in Enclosed Spaces," Seventh Tripartite Conference on Armaments, Explosives, & Propellants, U.S. Naval Ordnance Laboratory, White Oak, Silver Spring, Md., Sec. E-2, p. 89-104. April 1956.

19. Design of Structures to Resist Nuclear Weapons Effects. American Society of Civil Engineers, ASCE Manual of Engineering Practice No. 42. New York, 1961.

20. Armed Services Explosives Safety Board - Summary of Providing Wall Cubicle Tests April 1960 - April 1962. R.M. Rindner, A.H. Schwartz, S. Wachtell, Picatinny Arsenal, Dover, N.J., Technical Report No. 3292. October 1965.